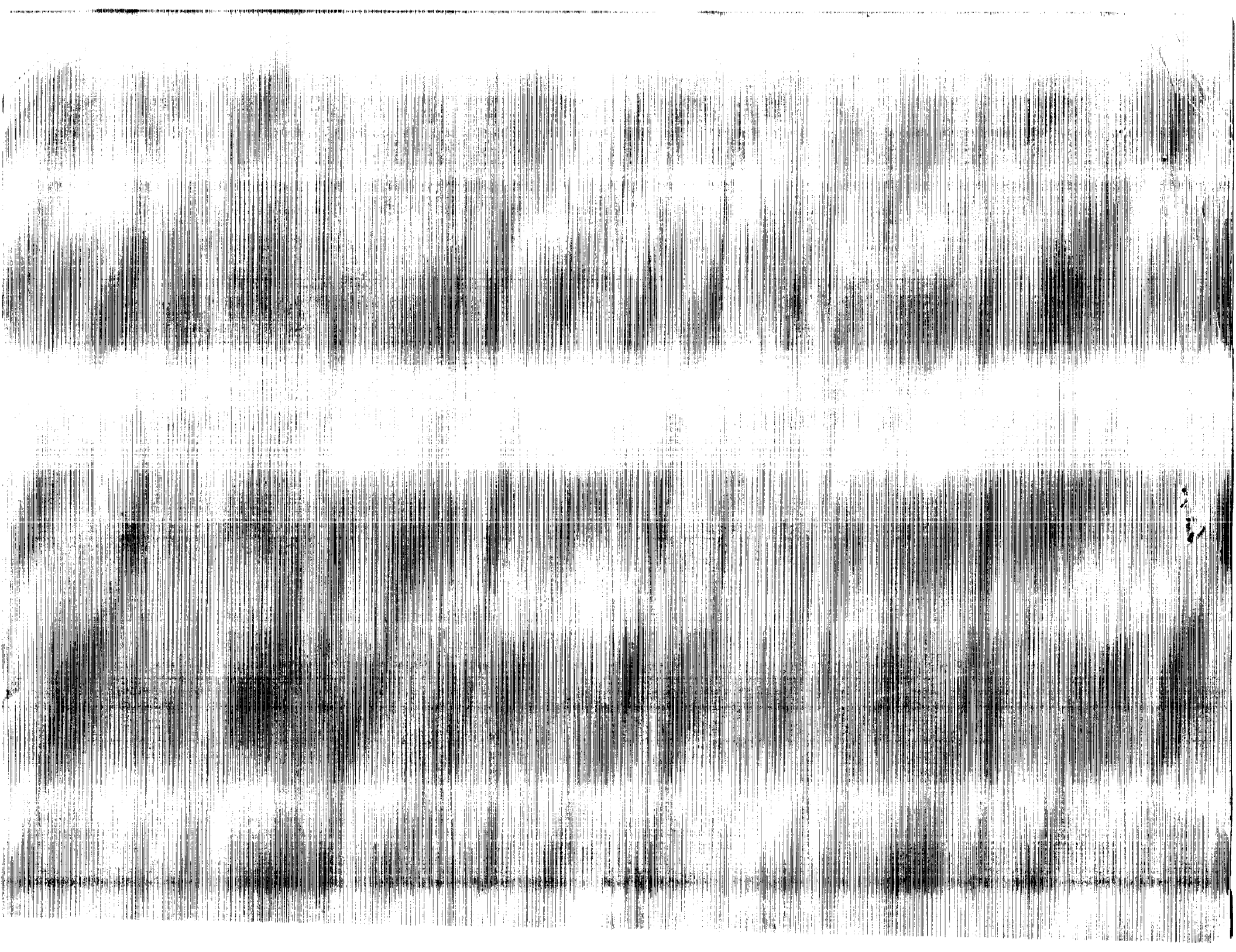


NASA CR-4313

Life, Development, and Reproduction of Ornithomimus and Related Lightning Events April 1968 at the University of New York

(NASA-CR-4313) JET, LUNATION, AND RATE OF
GROWTH OF NOCTURNAL LIGHTNING EVENTS
APPEARING ON SPACE SHUTTLE VIDEO TAPES Final
Report (State Univ. of New York) 250 P
CSCL 048 H1/47 Unclas 0303720



NASA Contractor Report 4313

Size, Duration, and Rate of Growth of Nocturnal Lightning Events Appearing on Space Shuttle Video Tapes

Christine Breslawski
State University of New York at Albany
Albany, New York

Prepared for
George C. Marshall Space Flight Center
under Contract NAS8-32893



National Aeronautics and
Space Administration
Office of Management
Scientific and Technical
Information Division

1990

ACKNOWLEDGMENTS

I would like to extend my thanks to the astronauts for taking the challenge of going into space and filming these lightning videos and to O. H. Vaughan, NASA Marshall Space Flight Center, for providing invaluable technical assistance during the analysis of the data. Thanks to Drs. Bernard Vonnegut and Vincent Idone for their helpful comments and suggestions. I am grateful to Lt. Mark Ahmadjian of the Air Force Geophysics Laboratory, Hanscom Air Force Base, for his help in obtaining the video tape from STS-51J, which included the interesting data on Typhoon Brenda. Finally, my sincere thanks to Dr. James C. Dodge for his interest in this research and for making it possible with funding through NASA Contracts NAS832893 and NAG8628.

This work is dedicated to the family and friends of those who lost their lives in the Space Shuttle Challenger disaster.

TABLE OF CONTENTS

	Page
ACKNOWLEDGMENTS	iii
LIST OF FIGURES	ix
LIST OF TABLES	xxiii
I. INTRODUCTION	1
II. MATERIALS AND METHODS	6
III. RESULTS	15
1. What do the Flashes Look Like?	16
2. Characteristics of the Lightning Flashes.	32
a) Duration.	32
b) Dimensions of the major and minor axes.	37
c) The area of the region illuminated by the flashes.	42
d) The rate of growth of the lightning.	43
3. The Maximum Area of an Event versus its Duration, the Time that the Maximum Area Occurred, and the Percent of the Total Lifetime of a Flash that Passed when the Maximum Area Occurred.	45
a) Maximum area versus the duration of a flash.	45
b) Maximum area versus the time that the maximum area occurred.	53
c) Maximum area versus the percent of the lifetime of the flash at which the maximum area occurred.	53
4. Changes in the Area of a Flash Over its Lifetime.	71
a) Peaks in the area curve.	71
b) The time interval between the peaks in the area curve.	72
c) Changes in the area between peaks.	77
d) The time to the first peak in the area curve versus the time to subsequent peaks.	80

e)	The change in the area versus the time interval from a minimum to peak in the area curve.	83
5.	The Bright Spot.	97
6.	Simultaneous Lightning Events.	99
7.	The Area Curves.	106
a)	The big ones.	106
b)	Periodic peaks.	117
c)	The area curves of flashes with average and below average size and duration.	117
d)	The area curves of simultaneous events.	125
e)	The shape of the area curves.	134
IV.	DISCUSSION	155
1.	Uncertainties in Lightning Measurements.	155
a)	Photogrammetric distortions.	155
b)	Interpretation of brightness and distinguishing the borders of an event.	156
c)	Video camera induced errors.	156
d)	Errors due to absorption and scattering.	157
2.	Composite Traces.	161
3.	Characteristics of the Lightning Events.	161
a)	Duration.	162
b)	Extent of the region illuminated by lightning.	163
c)	The rate of growth of the illumination.	169
4.	The Relationship Between the Maximum Area of a Flash and its Duration, the Time that the Maximum Area Occurred, and the Percent of the Total Lifetime of an Event at Which the Maximum Area was Attained.	170
a)	Duration versus the maximum area of a flash.	170
b)	When did the maximum area occur?	171
c)	The maximum area of a flash versus the percent of the total duration of the flash at which that maximum area occurred.	172

5.	The Peaks in the Area Curve.	173
a)	The number of peaks per flash.	173
b)	The time interval and absolute change in area between peaks in the area curve.	175
c)	The time interval to the first peak versus the time from subsequent minimums to peaks in the area curve.	176
d)	The time interval from a minimum to a peak in the area curve versus the change in the area during that time interval.	179
6.	Flashes which had the Bright Spot.	180
7.	Simultaneous Flashes.	182
8.	The Shape of the Area Curve.	185
V.	CONCLUSIONS	189
VI.	REFERENCES	194
	APPENDIX	199

LIST OF FIGURES

	Page
Figure 1: A lightning event, as it appears on the video monitor. The region below the limb of the earth represents space. Lines AEB, A'E'B', AA', and BB' mark the edges of the field of view of the camera.	12
Figure 2: A lightning event, as viewed from the space shuttle. The shaded, diagonally lined region represents the earth's surface. Lines AEB and A'E'B' correspond to lines AEB and A'E'B' in Figure 1.	13
Figure 3: Figures 3A through 3K show frames 1, 3, 7, 8, 10, 11, 13, 14, 15, 17, and 20 of simultaneous lightning events which appeared in the STS-9 video. The frame number is noted, along with the elapsed time in parentheses. In the initial frame (3A), the flash had dimensions of 9 km x 8 km. 233 ms later (3D), a second flash appears 25 km away. In the 20th frame (3K), yet another lightning event appears, 15 km away from the second event. Notice the hook shaped extension on the lower right of the initial event in Figures 3G-K. In Figure 3K, the approximate dimensions of the initial event are 34 km x 22 km. Those of the event in the center are 46 km x 17 km, while those of the the third event are 4.5 km x 4.5 km.	19
Figure 4: A composite trace of one of the flashes from STS-51J, which was photographed with a 150 mm zoom lens. The initial trace of this event is labeled 33. The subsequent traces are labeled according to when they appeared after frame 0 (the frame preceding frame 33 in which no flash was present).	20
Figures 5A and B: Figure 5A is a composite trace of flash 11 from STS-9. Contours are labeled as explained in Figure 4. Notice that this event grows in a favored direction. That is, its greatest size increase occurs along an axis from the top to the bottom of the page. Figure 5B is a composite trace of two simultaneous events from STS-9. These two events were approximately 6 km apart when they first appeared.	22
Figures 6A and B: Contours for both A and B are labeled as explained in Figure 4. Figure 6A is a composite trace of flash 15 of STS-8. The hatched region indicates the location of a persistent bright spot which appeared in a small percentage of all 323 events. Figure 6B is a composite trace of flash 2 from STS-41D. Note that the initial frame of flash 2 is also its largest.	24

Figures 7A and B: Contours for both A and B are labeled as explained in Figure 4. Figure 7A shows the composite traces of two simultaneous events from the STS-51J video. These two events were 80 km apart when they first appeared together. Figure 7B shows a series of simultaneous events, also from the STS-51J video. Events 101, 102, and 103, and events 103 and 104 occurred together.

25

Figures 8A and B: Contours for both A and B are labeled as explained in Figure 4. Figure 8A is a composite trace of three simultaneous events from the STS-51J video. Flashes 112 and 113, and 113 and 114 were 20 km and 130 km apart, respectively, when they first appeared. Figure 8B is a composite trace of a series of six simultaneous flashes from the STS-51J video, which occurred over a 1066 ms time period. The greatest number of events appearing at any one time in this series of events was four. Note that event 172, represented by the broken line, appeared near the same location as event 170, but 200 ms later.

27

Figure 9: The duration of a flash (in 33.3 ms time intervals) versus the number of flashes with a given duration, for all 323 events. The average duration of all events was 400 ms.

33

Figure 10: The duration of a lightning event (in milliseconds) versus the percent of flashes whose lifetime was longer than the duration of a given event, for all 323 flashes. The curve was calculated by a 9th order regression.

34

Figures 11A - C: The duration of a flash (in 33.3 ms time intervals) versus the number of flashes with a given duration, for STS-8 and STS-41D, STS-9, and STS-51J (Figures 11A, 11B, and 11C, respectively). The events of STS-8 and STS-41D were combined because of the small number of events in each data set. The average flash duration for STS-8, STS-41D, STS-9, and STS-51J was 587 ms, 312 ms, 350 ms, and 416 ms, respectively.

36

Figures 12A - C: The duration of a lightning event (in milliseconds) versus the percent of flashes whose lifetime was longer than the duration of a given event, for the flashes of STS-8 and STS-41D, STS-9, and STS-51J (Figures 12A, 12B, and 12C, respectively). The curves for STS-8 and STS-41D, STS-9, and STS-51J were calculated by 5th order, 7th order, and 10th order linear regressions, respectively.

39

Figures 13A and B: Figure 13A shows the duration of a flash (ms) versus the maximum area attained by that event (km^2), for all events. Figure 13B is an enlargement of the region in 13A which is bounded by 1200 ms and 15000 km^2 . STS-8 events (+), STS-9 events (x), STS-41D events (\diamond), STS-51J events (\circ), STS-51J with zoom lens (STS-51Jz) (Δ). 46

Figures 14A and B: Figure 14A shows the duration of a flash (ms) versus the maximum area attained by that event (km^2), for the events of STS-51J. Figure 14B is an enlargement of the region in 14A which is bounded by 1200 ms and 10000 km^2 . 47

Figures 15A and B: Figure 15A shows the duration of a flash (ms) versus the maximum area attained by that event (km^2), for the events of STS-9. Figure 15B is an enlargement of the region in 15A which is bounded by 800 ms and 600 km^2 . 49

Figures 16A and B: Figure 16A shows the average value of the maximum area (km^2) attained by all events with a given duration, versus the duration of those events (ms), for all flashes. The curve was calculated via a 1st order linear regression. Error bars indicate one standard deviation from the mean maximum area. Figure 16B is the same, except that the outlying point at 1833 ms has been omitted. Points without error bars, and with durations of 600 ms or greater, consisted of only one data point before averaging the area. Points without error bars and with durations less than 600 ms had standard deviations which were smaller than the resolution of the computer plotter. 50

Figures 17A and B: Same as Figure 16A and B, except that average maximum area values (km^2) are calculated for only the events of STS-51J. 51

Figure 18: Same as Figure 16A, except that the average maximum area values (km^2) are calculated for only the events of STS-9. 52

Figure 19: The number of lightning events which attained their maximum area at a given time, versus the time (ms) that the maximum area occurred, for all flashes. 54

Figures 20A and B: Figure 20A shows the maximum area of a flash (km^2), versus the time that the maximum area occurred (ms), for all events. Figure 20B is an enlargement of the region in 20A which is bounded by 900 ms and 15000 km^2 . STS-8 (+), STS-9 (x), STS-41D (\diamond), STS-51J (\circ), STS-51Jz (Δ) 55

Figures 21A and B: Figure 21A shows the maximum area of a flash (km^2), versus the time that the maximum area occurred (ms), for the events of STS-51J. Figure 21B is an enlargement of the region in 21A which is bounded by 900 ms and 10000 km^2 . 57

Figures 22A and B: Figure 22A shows the maximum area of a flash (km^2), versus the time that the maximum area occurred (ms), for the events of STS-9. Figure 22B is an enlargement of the region in 22A which is bounded by 600 ms and 500 km^2 . 58

Figures 23A and B: Figure 23A shows the time (ms) at which the maximum area of a flash occurred, versus the average value of the maximum area (km^2) of all events reaching their maximum area at a given time, for all 323 flashes. The error bars indicate one standard deviation from the mean area. The curve was calculated via a first order linear regression. Points without error bars consisted of one value of maximum area before averaging. Figure 23B is the same as 23A except that the point at 1266 ms has been omitted. 60

Figures 24A and B: Figure 24A is the same as Figure 23A, except that the mean maximum area values are calculated only for the events of STS-51J. Figure 24B is the same as 24A, except that the outlying point at 966 ms has been omitted. 61

Figure 25: Figure 25 is the same as Figure 23A, except that the mean maximum area values are calculated only for the events of STS-9. 62

Figures 26A and B: Figure 26A shows the maximum area of a flash (km^2), versus the percent of the total duration of that flash at which the maximum area occurred. Figure 26B is an enlargement of the region in 26A bounded by 8000 km^2 and 100%. STS-8 (x), STS-9 (\diamond), STS-41D (+), STS-51J and 51Jz (o). 64

Figures 27A and B: Figure 27A is the same as Figure 26A, except that only those points from the STS-51J lightning events are shown. Figure 27B is an enlargement of the region in 27A which is bounded by 8000 km^2 and 100%. 65

Figures 28A and B: Figure 28A is the same as Figure 26A, except that only those points from the STS-9 lightning events are shown. Figure 28B is an enlargement of the region in 28A which is bounded by 300 km^2 and 100%. 66

Figure 29: Figure 29 indicates the number of flashes whose maximum area occurred at a given percent of their total duration. The number of flashes has been summed over each 10% interval. 68

Figures 30A, B, and C: Figures 30A - C show the mean value of the maximum area (km^2) of the events, which attained their maximum area within a given percent of their total duration, for all events, the events of STS-51J, and the events of STS-9, respectively. To attain the mean areas, the areas plotted in Figures 26 - 28 were averaged for each 10% interval. 70

Figure 31: The length of the time interval between two peaks in the area curve of an event (ms), versus the percent of all interpeak time intervals with a given duration, for all 323 flashes. 74

Figure 32A and B: The length of the time interval between two peaks in the area curve of an event (ms), versus the percent of all interpeak time intervals with a given duration, for the events of STS-51J (Figure 32A) and those of STS-9 (Figure 32B). 75

Figure 33A and B: The length of the time interval between two peaks in the area curve of an event (ms), versus the percent of all interpeak time intervals with a given duration, for the events of STS-8 (Figure 33A) and those of STS-41D (Figure 33B). 76

Figures 34A-D: Figures 34A-D show the time interval between two peaks in the area curve versus the average of the absolute change in area that occurred during that time period for flights STS-51J, STS-9, STS-41D, and STS-8, respectively. The error bars indicate one standard deviation from the average area. Points without error bars consisted of only one value before averaging. The curve was calculated by a first order linear regression. With the exception of the STS-8 events, as the time interval increases, the average of the absolute change in area between two successive peaks also increases. 79

Figure 35: The time interval (ms) to the initial peak in the area curve (o), and the time interval (ms) between all other minimums to the following peak in the area curve (Δ) versus the percent of values with a given minimum to peak area time interval, for all 323 lightning events. At 100 ms and 200 ms, the two data sets overlap. Notice the shift to a greater percent of smaller values for the time interval between the subsequent minimum to peak in the area curve. 81

Figure 36A and B: Same as Figure 35, but for the events of STS-51J (Figure 36A) and those of STS-9 (Figure 36B). Note that the data sets overlap at 166 ms in Figure 36A, and at 100 ms in Figure 36B.	82
Figures 37A and B: Same as Figure 35, but for the events of STS-8 (Figure 37A), and STS-41D (Figure 37B).	84
Figures 38A and B: Figure 38A shows the time interval from a minimum to a peak in the area curve (ms), versus the change in the area (km^2) over that time interval, for all 323 events. Figure 38B is an enlargement of the region in 37A which is bounded by 300 ms and 6000 km^2 . STS-8 (+), STS-9 (Δ), STS-41D (x), STS-51J and 51Jz (\circ)	86
Figure 39: The average of the change in area (km^2) (shown in Figures 38A and B) during a given minimum to peak time interval, versus that time interval (ms), for all 323 events.	87
Figures 40A and B: Figure 40A is the same as Figure 38A, except that only the STS-51J data points are shown. Figure 40B is an enlargement of the region in 40A which is bounded by 300 ms and 6000 km^2 .	89
Figures 41A and B: Figure 41A is the same as Figure 38A, except that only the STS-9 data points are shown. Figure 41B is an enlargement of the region in 41A which is bounded by 300 ms and 300 km^2 .	90
Figures 42A and B: Figure 42A is the same as Figure 38A, except that only the STS-8 data points are shown. Figure 42B is an enlargement of the region in 42A bounded by 300 ms and 5000 km^2 .	91
Figure 43A and B: Figure 43A is the same as Figure 38A, except that only the STS-41D data points are shown. Figure 43B is an enlargement of the region in 43A which is bounded by 6500 (km^2) and 300ms. Note that none of the minimum to the following peak in the area curve time intervals lasted longer than 100 ms.	93
Figures 44A and B: Figure 44A shows the time interval from a minimum to peak in the area curve (ms), versus the average change in area (km^2) over a given time interval, for the events of STS- 51J. The curve was calculated by a first order linear regression. The error bars indicate one standard deviation from the mean area. Figure 44B is the same as 44A, except that it is for the events of STS-9.	94

Figures 45A and B: Figures 45A and B are the same as Figure 44A, except that they are for the events of STS-8 and STS-41D, respectively. 95

Figure 46: The distance between two simultaneous events (km), versus the number of pairs of simultaneous events a given distance apart. The number of events has been summed for each 10 km interval. The distance between two events was measured on the initial video frame in which both flashes appeared. When more than two events were simultaneous, the distance was measured between the two closest events. 101

Figure 47: The number of lightning events appearing at one time, versus the percent of events which appeared in a group larger than any given number of events. The curve was calculated by a cubic spline. The curve is shown for all flashes, as well as for the events of STS-41D, STS-51J, and STS-9. At 5 and 6 flashes appearing in a video frame, the symbols for STS-9 events and all events overlap. 103

Figure 48: The number of events appearing together in a video frame versus the number of flashes which appeared in a given grouping. This is shown for all events together, as well as for the events of STS-9, STS-41D, and STS-51J. 104

Figure 49: Figure 49 shows the percent of all simultaneous events which occurred in a group of coincident events, of a given size. There aren't any data points for the x-value of 1, because one event appearing alone is not simultaneous with any other event. At four flashes occurring simultaneously the data points for STS-9, STS-51J, and all flashes overlap. 105

Figure 50: This figure shows the fluctuations in the area of a flash over its lifetime, for the first five events from STS-41D. These events were not simultaneous. Events 2, 3, and 4 are three of the nine events whose maximum area exceeded $10,000 \text{ km}^2$. (Flash 1: solid curve; Flash 2: long dash curve; Flash 3: short dash curve; Flash 4: dotted curve; Flash 5: dash-dot curve). 108

Figure 51: This figure shows the fluctuations in the area of a flash over its lifetime, for flashes 56 and 57 of STS-51J. These two simultaneous events were 95 km apart. (Flash 57: solid curve; Flash 58: broken curve). 109

Figure 52: This figure shows the fluctuations in the area of a flash over its lifetime, for flash 70 of STS-51J. 111

Figure 53: This figure shows the fluctuations in the area of a flash over its lifetime, for simultaneous flashes 84 through 89 of STS-51J. Events 84/85, 84/86, and 84/87 were 70 km, 5 km, and 210 km apart, respectively. Events 84/88 and 84/89 were 170 km and 110 km apart, respectively. Event 84 had the longest duration and largest number of peaks in the area curve, of all 323 flashes. (Flash 84: solid curve; Flash 85: long dash curve; Flash 86: short dash curve; Flash 87: dotted curve; Flash 88: dash-dot curve; Flash 89: dash-square curve).

112

Figure 54: This figure shows the fluctuations in the area of a flash over its lifetime, for simultaneous events 134 and 135 of STS-51J. These two events were 100 km apart. Flash 134 was the largest of all 323 lightning events, with maximum dimensions of approximately 440 km x 110 km. (Flash 134: solid curve; Flash 135: broken curve).

113

Figure 55: This figure shows the fluctuations in the area of a flash over its lifetime, for events 1 through 5 of STS-8. These events were not simultaneous. Flash 2 was the largest of all STS-8 events. Flashes 1 - 3 had the bright spot that was mentioned in the text. (Flash 1: solid curve; Flash 2: long dash curve; Flash 3: short dash curve; Flash 4: dotted curve; Flash 5: dash-dot curve).

115

Figure 56: This figure shows the fluctuations in the area of a flash over its lifetime, for events 6 through 10 of STS-8. These events were not simultaneous. Events 9 and 10 had the longest duration of all STS-8 events. The bright spot appeared in events 6, 9, and 10. (Flash 6: solid curve; Flash 7: long dash curve; Flash 8: short dash curve; Flash 9: dotted curve; Flash 10: dash-dot curve).

116

Figure 57: This figure shows the fluctuations in the area of a flash over its lifetime, for simultaneous events 11 and 12 of STS-51J. These two events were 260 km apart. Notice the almost constant time interval between the peaks in the area curve of flash 11. (Flash 11: solid curve; Flash 12: broken curve).

118

Figure 58: This figure shows the fluctuations in the area of a flash over its lifetime, for events 16 through 20 of STS-9. These events were not simultaneous. Events 16 and 18 have the largest and smallest maximum area of all STS-9 events, respectively. (Flash 16: solid curve; Flash 17: long dash curve; Flash 18: short dash curve; Flash 19: dotted curve; Flash 20: dash-dot curve).

119

Figure 59: This figure shows the fluctuations in the area of a flash over its lifetime, for events 86 through 89 of STS-9. These events were not simultaneous. Flashes 86 through 89 were some of the smallest STS-9 events. They also had some of the shortest durations of all STS-9 flashes. Note the variation in the number of peaks in the area curves. The curves of flashes 87 and 88 overlap during the last 33ms. (Flash 86: solid curve; Flash 87: long dash curve; Flash 88: short dash curve; Flash 89: dotted curve). 121

Figure 60: This figure show the fluctuations in the area of a flash over its lifetime, for simultaneous events 5 and 6 of STS-9. These two events were 2 km apart. Flash 5 had two bright spots, while flash 6 had one. (Flash 5: solid curve; Flash 6: broken curve). 122

Figure 61: This figure shows the fluctuations in the area of a flash over its lifetime, for events 50 and 63 of STS-9. These two events were not simultaneous. Flash 63 had the longest duration, and most peaks in the area curve of all STS-9 events, while flash 50 had a duration which is typical of the average STS-9 event. (Flash 50: solid curve; Flash 63: broken curve). 123

Figure 62: This figure shows the fluctuations in the area of a flash over its lifetime, for events 1 through 4 of STS-51J. These events were not simultaneous. They illustrate the variation in the size, duration, and number of peaks in the area curve of the STS-51J events. (Flash 1: solid curve; Flash 2: long dash curve; Flash 3: short dash curve; Flash 4: dotted curve). 124

Figure 63: This figure shows the fluctuations in the area of a flash over its lifetime, for events 142 through 144 of STS-51J. These events were not simultaneous. These curves show some of the events of STS-51J which had a short duration. Notice that the time interval to the largest area is shorter than the remainder of the duration of these flashes. (Flash 142: solid curve; Flash 143: long dash curve; Flash 144: short dash curve). 126

Figure 64: This figure shows the fluctuations in the area of a flash over its lifetime, for simultaneous events 43 and 44 of STS-51J. These two events were 130 km apart. Event 43 is typical of an average STS-51J flash in its size, duration, and number of peaks in the area curve. (Flash 43: solid curve; Flash 44: broken curve.) 127

Figure 65: This figure shows the fluctuations in the area of a flash over its lifetime, for simultaneous events 6 through 8 of STS-41D. The distance between events 6/7 was 25 km, while that between events 7/8 was 5 km. The lifetimes of events 7 and 8 occurred within the lifetime of event 6. (Flash 6: solid curve; Flash 7: long dash curve; Flash 8: short dash curve).

129

Figure 66: This figure shows the fluctuations in the area of a flash over its lifetime, for simultaneous events 31 and 32 of STS-51J. These two events were 50 km apart. (Flash 31: broken curve; Flash 32: solid curve).

130

Figure 67: This figure shows the fluctuations in the area of a flash over its lifetime, for simultaneous events 9 and 10 of STS-51J. These two events were 150 km apart. (Flash 9: solid curve; Flash 10: broken curve).

131

Figure 68: This figure shows the fluctuations in the area of a flash over its lifetime, for simultaneous events 59 through 65 of STS-51J. Near 400 ms, four of these events were active at the same time. The distance between events 59/60, 59/61, and 61/62 was 10 km, 5 km, and 115 km, respectively. The distance between events 60/63, 64/62, and 63/65 was 60 km, 20 km, and 20 km, respectively. (Flash 59: solid curve; Flash 60: long dash curve; Flash 61: short dash curve; Flash 62: dotted curve; Flash 63: dash-dot curve; Flash 64: dash-square curve; Flash 65: dash-circle curve).

132

Figure 69: This figure shows the fluctuations in the area of a flash over its lifetime, for simultaneous events 25 through 30 of STS-9. The curve for event 29 lies near the lower axis. At 133 ms, six events were active at the same time. The distance between events 25/26, 26/27, 27/28, 26/29, and 25/30 was 10 km, 10 km, 15 km, 15 km, and 30 km, respectively. (Flash 25: solid curve; Flash 26: long dash curve; Flash 27: short dash curve; Flash 28: dotted curve; Flash 29: dash-dot curve; Flash 30: dash-square curve).

133

Figure 70: This figure shows the fluctuations in the area of a flash over its lifetime, for simultaneous events 38 and 39 of STS-9. These two events were 10 km apart. Both had a bright spot. (Flash 38: solid curve; Flash 39: broken curve).

135

Figure 71: This figure shows the fluctuations in the area of a flash over its lifetime, for simultaneous events 66 through 68 of STS-9. Events 66/67, and 67/68 were separated by 5 km and 4 km, respectively. (Flash 66: solid curve; Flash 67: long dash curve; Flash 68: short dash curve).

136

Figure 72: This figure shows the fluctuations in the area of a flash over its lifetime, for event 5 of STS-51J. The curve of this event illustrates the 'horn' shaped curve. 138

Figure 73: This figure shows the fluctuations in the area of a flash over its lifetime, for simultaneous events 151 and 152 of STS-51J. These two events were 150 km apart. Flash 151 has a 'horn' type curve, while the curve of flash 152 was classified as a maximum area near the end of the lifetime curve. (Flash 151: solid curve; Flash 152: broken curve). 139

Figure 74: This figure shows the fluctuations in the area of a flash over its lifetime, for simultaneous events 44 through 46 of STS-9. Flashes 44/45, and 44/46 were separated by 8 km, and 9 km, respectively. Curve 45 is an example of a 'mirror image' curve, curve 46 is an example of a maximum peak in the middle curve, and curve 44 is an example of a curve which does not fit into any of the specified shape categories. (Flash 44: solid curve; Flash 45: long dash curve; Flash 46: short dash curve). 140

Figure 75: This figure shows the fluctuations in the area of a flash over its lifetime, for events 98 through 100 of STS-51J. These events were not simultaneous. The curves for events 98 and 100 are examples of the maximum peak at the beginning of the lifetime category. Note how each successive peak of these two curves gets smaller. (Flash 98: solid curve; Flash 99: long dash curve; Flash 100: short dash curve). 142

Figure 76: This figure shows the fluctuations in the area of a flash over its lifetime, for event 37 of STS-51J. This curve is an example of the maximum peak near the beginning of the lifetime shape category. 143

Figure 77: This figure shows the fluctuations in the area of a flash over its lifetime, for events 131 through 133 of STS-51J. These events were not simultaneous. Flashes 131 and 133 have curves which fall into the maximum area at or near the end of the duration category, while the curve of flash 132 was classified as bimodal. (Flash 131: solid curve; Flash 132: long dash curve; Flash 133: short dash curve). 145

Figure 78: This figure shows the fluctuations in the area of a flash over its lifetime, for events 1 through 3 of STS-51Jz, (the events of STS 51J which were photographed with the zoom lens). They did not occur simultaneously. The curves illustrate the trend of successively larger peaks in the area curve over time. (Flash 1: solid curve; Flash 2: long dash curve; Flash 3: short dash curve). 146

Figure 79: This figure shows the fluctuations in the area of a flash over its lifetime, for simultaneous events 179 and 180 of STS-51J. Curve 179 is an example of a maximum peak near the end of the flash duration type curve, while the area curve of event 180 is an example of a maximum peak in the middle curve. These two events were 30 km apart. (Flash 179: solid curve; Flash 180: broken curve). 147

Figure 80: This figure shows the fluctuations in the area of a flash over its lifetime, for simultaneous events 14 and 15 of STS-51J. These two events were 40 km apart. Both curves fall into the maximum area near the middle shape category. (Flash 14: solid curve; Flash 15: broken curve). 148

Figure 81: This figure shows the fluctuations in the area of a flash over its lifetime, for events 93 and 94 of STS-9. These two events did not occur simultaneously. Curve 93 is an example of the maximum area at the end type curve, while curve 94 is an example of the maximum area near the middle type curve. (Flash 93: solid line; Flash 94: broken curve). 150

Figure 82: This figure shows the fluctuations in the area of a flash over its lifetime, for flash 53 of STS-51J. This curve does not fit into any of the first four shape categories given in the text. 151

Figure 83: The percentage of the 323 area curves which fall into a given shape category. Each major category, denoted by a number, is further divided into its subclasses. 153

Figure A1: The geometric conversion of a distance D , on the video monitor, to an angle ψ in the field of view of the camera. ψ is the angle between the normal to the principal point P and a ray from point L to any X location. θ is the angle between the normal to the principal point P and a ray from L to any Y location, and is calculated in a similar manner to angle ψ . ψ_{Hmax} is equal to one-half the horizontal field of view, and ψ_{Vmax} is equal to one-half the vertical field of view. The focal length of the camera is represented by f . 200

Figure A2: The geometric conversion of an angle in the field of view to an actual earth distance. The shuttle is at an altitude H above the earth of radius R . Every angle $d\psi$ has a corresponding angle $d\phi$. The actual dimensions of a flash, dS_θ and dS_ψ are found using equations 8a and 8b. This conversion is used when the camera is looking at nadir. 203

Figure A3: When the camera is tilted from nadir, then large distance distortions occur in the direction in which the camera is tilted. Consider an angle $d\theta$, taken at two different places within the field of view of the camera. Although the distances on the image plane, D_1 and D_2 , are equal, the corresponding actual distances, S_1 and S_2 are not equal.

205

Figure A4: The geometric conversion of an angle θ , in the field of view, to the angle ϕ . The shuttle is at an altitude H above the earth of radius R . In this case, the camera is tilted from nadir. $2\theta_{Vmax}$ is the vertical field of view. The angle θ is measured from the ray A' , which is a ray within the field of view that is tangent to the limb of the earth.

206

Figure A5: The geometric conversion of the angles $d\theta$ and $d\psi$, in the camera field of view to the actual dimensions of a lightning event. For every $d\theta$ there is a corresponding $d\phi$. The dimension of the flash which is perpendicular to the limb of the earth, dS_0 , can be found using equation 8a. The dimension of the flash in the direction parallel to the limb of the earth, dS_ψ , is calculated by equation 14. The dashed line denotes the edge of the vertical field of view.

208

LIST OF TABLES

	Page
Table IA-D: Flight information and camera parameters for each data set. Latitude and longitude give an approximate shuttle location during filming of the lightning events.	
Table IA: Flight STS-8	9
Table IB: Flight STS-9	9
Table IC: Flight STS-41D	10
Table ID: Flight STS-51J	10
Table II: Initial major and minor axes dimensions of lightning for all events and for those of each flight.	40
Table III: Average largest major and minor axes dimensions, and average initial and maximum area for all flashes and for each flight.	41
Table IV: Average rate of growth from initial to largest major and minor axes dimensions for all flashes and for each flight.	44
Table V: Peak in the area curve - A summary of the number of peaks per flash, and the time interval between two peaks, to the first peak, and between a minimum and the subsequent peak in the area curve.	73
Table VI: Some characteristics of flashes which had a very bright spot. 'With' refers to the average values for flashes with the bright spot, and 'without' refers to the average values for flashes without the bright spot.	98

I. INTRODUCTION

Observations of nocturnal lightning events from space have been reported by astronauts. These eyewitness accounts, published in Cooper (1976), Vonnegut (1979), and Vonnegut et al. (1984), give an estimate of the size and frequency of nocturnal lightning as viewed from above. These reports also give descriptions of the occurrence of nearly simultaneous, or sympathetic lightning events separated by hundreds of kilometers. In a personal correspondence, astronaut Bob Cenker (1986) gave the following description of thunderstorm activity over Africa, which he observed while on shuttle flight STS-61C.

"While I was not specifically documenting this phenomenon, I could not help but be impressed by the sight. What particularly caught my attention (other than the lack of thunder), was the frequency of the lightning strikes; not unlike popcorn. Trying to be more qualitative, I would estimate 1-2 events per second in the available viewing area. Based on approximate overhead window dimensions, and viewing geometry, I estimate that viewing area to be approximately 30,000 square miles. I do not recall actually seeing lightning strikes, per se: but rather an "instantaneous" (or at least very short lived) illumination of the clouds. This illumination appeared to be approximately the size of a quarter, which I estimate to be an approximate 10 mile diameter on the ground. As we passed over the area I noticed no "bunching" or concentration of activity."

The U-2 high altitude aircraft has been used for observing nocturnal lightning events while flying over the tops of thunderstorms. Lightning events observed during the U-2 flights were photographed with Vinten cameras, and a TV camera with a Charge Coupled Device (CCD). These cameras observed a region of approximately 10 km x 10 km. From an average altitude of 20 km, the cameras aboard the U-2 aircraft recorded the cauliflower like structure of the tops of thunderstorms, which were visible when illuminated by lightning. Lightning channels which terminated in clear air above the storm, as well as parts of the channel traveling from one region of a cloud to another were also observed (Brook et al., 1984, Christian et al., 1983, and Vaughan, 1984). The optical pulse characteristics, electric field changes, and spectral characteristics produced by lightning have been recorded using instruments flown on the U-2 aircraft (Brook et al., 1980).

The Orbiting Solar Observatory Satellite (OSO-2 and OSO-5) and Vela Satellites have been applied to the observation of global lightning activity (Sparrow and Ney, 1971, Turman, 1977, Turman, 1979, and Orville, 1982). More recently, data recorded by the optical detectors on the Defense Meteorological Satellite Program (DMSP) Satellites have been used to investigate the global distribution of lightning. Average yearly global flash rates have been estimated to be 40 - 120 flashes per second (Orville, 1986). Studies using the DMSP optical data, have shown diurnal trends in lightning activity, variation in the location and frequency of lightning events at dawn and dusk, an annual march of lightning

north and south that corresponds to the seasons, a lack of lightning activity over the oceans, average land to ocean lightning ratios, and yearly, monthly, and seasonal changes in lightning activity at a given location (Edgar, 1983, Turman and Edgar 1982, Orville, 1981, and Orville and Henderson, 1986).

The space shuttle offers yet another viewing platform for lightning observations. Traveling at a height of 200 km - 500 km, the shuttle falls between the observational altitudes of the U-2 aircraft, which flies directly over the tops of thunderstorms, and the DMSP satellite, which travels at an average altitude of 830 km. When directed at nadir, the space shuttle camera offers a viewing area of approximately 10000 km^2 , with a spatial resolution of 1 km. The video advances at a rate of 30 frames per second. In contrast, the U-2 cameras offer a viewing area of 100 km^2 , and a spatial resolution of 0.5 km. Each frame of the film was exposed for 11 seconds. The DMSP satellite detects lightning events on a global scale, and has a scanner with a spatial resolution of 100 km. The time resolution, however, is not great enough to resolve the evolution of a lightning event.

The first formal documentation of observations of lightning discharges from the space shuttle was conducted on flight STS-2 in November, 1981 as part of the Office of Space and Terrestrial Applications Experiments known as OSTA-1. The OSTA-1 payload consisted of seven experiments designed for the remote sensing of land resources, environmental quality, ocean conditions, and meteorological phenomena (Baldwin et al., 1981). One experiment in

OSTA-1, the Nighttime/Daytime Optical Survey of Lightning Experiment (NOSL), was designed to photograph both day and nighttime thunderstorms using a 16 mm data acquisition camera (Vonnegut, 1982 and Vonnegut et al., 1983a.) A photocell optical system was used simultaneously with the camera to detect daytime, as well as nighttime lightning events. The signals detected by the photocell optical system were recorded on a magnetic tape. The camera and the attached optical system were hand held by an astronaut who operated them from the flight deck of the shuttle.

The NOSL experiment was flown on subsequent shuttle missions STS-4 and STS-6. Although there was only approximately twenty minutes of total nighttime observation on the three flights combined, many interesting characteristics of the lightning events were found (Vonnegut et al. 1983b, 1984, and 1985). Flash dimensions were found to range from ten to one-hundred kilometers. The rate of propagation of the illumination for most events was on the order of 10^5 m/sec, and flash duration was as long as 1.6 seconds. Some interesting geometric shapes of the illumination, such as a y-shaped flash, were also observed (Vonnegut et al., 1983b). Stereo pictures, produced from the daytime photography, showed convective cloud structure.

This study is an unofficial continuation of the NOSL experiment. At the suggestion of Mark Ahmadjian, of the Air Force Geophysics Laboratory (AFSC), the astronauts were asked to photograph any regions of lightning activity over which they were passing, using a video camera that was mounted in the payload bay

of the shuttle. The data for this study was obtained on flights STS-8, STS-9, STS-41D, and STS-51J. The four video tapes cover a total time period of 10.5 minutes. This study involves the analysis of 323 flashes. No lightning channels were visible on the video tape; what was seen was a diffuse illumination of the clouds by the lightning flashes.

The objectives of this study were to find the linear extent of these flashes, their maximum area, duration, the rate of propagation of the illumination, and the relationship between the size and duration of these flashes. Groups of flashes which were spatially distant from each other (10 to 10^2 km), and that appeared at, or nearly at the same time were investigated. The change in the area of an event over its lifetime was also examined.

II. MATERIALS AND METHODS

The procedure for filming nocturnal lightning from the shuttle was conducted as follows. Several ninety minute orbits prior to passing over a region of thunderstorm activity, the astronauts were notified on the basis of weather data of the opportunity for filming lightning. Provided that the astronauts were not occupied with a pre-scheduled activity, the lightning flashes were photographed with video cameras which were mounted in the payload bay. The angle of the camera with respect to nadir and the direction in which it was pointed were not recorded. This led to some difficulties in the analysis of the data which will be discussed later in this section. With the exception of the STS-51J video, the mission elapsed time was superimposed on each frame of the videotape.

Flight STS-8 was launched on 30 August 1983. The video pictures were filmed on 4 September from 03:11:32 GMT to 03:12:33 GMT at a height of 222 km. A RCA SIT (Silicon Intensified Target) video camera with a 16 mm focal length and a 46° diagonal field of view was used. The camera was mounted on the rear bulkhead of the shuttle and had automatic iris and gain controls. The lightning events were photographed over the Gulf of Mexico, approximately 300 km west of Florida.

Flight STS-9 was launched on 28 November 1983. Nocturnal lightning events were photographed at a height of 250 km on 2 December from 11:38:25 GMT TO 11:41:37 GMT. The flashes were located near 33° S latitude, 34° W longitude over the South Atlantic

Ocean, east of Uruguay. A SEPAC SIT low light monochrome vidicon camera, similar to that flown on Spacelab 1, was used. The camera was mounted on a two axis gimbal. The vidicon camera had a 28.7° horizontal field of view, a 21.7° vertical field of view, and a focal length of 25 mm. The spectral response of the camera was 390-700 nanometers. The camera had a fixed focus, auto iris, and a sensitivity of $0.01 \text{ lux} - 10^5 \text{ lux}$. The camera sensor was a 16mm silicon SIT target. The video had a line rate of 15.73Hz and a 4.5MHz video bandwidth.

Flight STS-41D was launched on 30 August 1984. The video tape images of lightning were filmed at an average height of 314 km from 14:09:35 GMT to 14:12:25 GMT on 1 September. An 18 mm focal length SIT video camera with a 51.5° diagonal field of view was used. The flashes were located northwest of New Guinea, near 2° S latitude, 150° E longitude.

Flight STS-51J was launched 3 October 1985. The lightning was filmed from an average height of 502 km. The exact time and location of filming is unknown because this information was classified at the time this thesis was written. The video lasted 210 seconds. What is known is that the video was taken over typhoon Brenda near Sri Lanka. An IT&T Model 4561 video camera with an intensified Charge Injected Device (CID) was used. The CID differs from the SIT in that it has a spectral response of 400-800 nanometers, with a peak spectral response at the 580-750 nanometer range. There is also less blooming of bright images when a CID is used. The IT&T camera had a 25 mm focal length, 19.9° horizontal field of view,

and a 15.03° vertical field of view. The camera had an auto iris, and a sensitivity of 10^{-6} foot candles. The video camera resolution was 244×388 pixels with 18 line pairs per millimeter. A segment of the STS-51J video was taken with a zoom lens which had a 150mm focal length, a 3.3° horizontal field of view, and a 2.5° vertical field of view.

Table I.A - D presents a summary of the data for each flight, along with a list of the camera parameters. In flights STS-8, 9, and 51J the camera was mounted in the payload bay. During flight STS-41D the camera was mounted on the wrist of the Remote Maneuvering System (RMS) more commonly known as the "Canadian Arm." In all flights the video cameras had a frame advance rate of 30 frames/second, thus exposing each frame for 33.333 milliseconds.

In order to analyze the lightning flashes, the video images were initially projected onto a plate of clear glass mounted in a frame, using a magnifying lens that was mounted in a piece of blackened cardboard. Both the clear glass and lens were positioned parallel to the front of the video monitor. Blackened cardboard was extended forward from the top, bottom, and sides of the monitor to the lens in order to concentrate the light from the monitor. However, even in a darkened room, the image projected by the magnifying lens was too faint to be traced onto a thin paper. Therefore, the flashes were traced directly off the video monitor. The video tape was advanced frame by frame, and the outer borders of the illumination from the lightning were traced onto thin paper. If the limb of the earth appeared in a video frame containing

Tables I.A - D:

Flight Information and Camera Parameters for Each Data Set.
Latitude and longitude give an approximate shuttle location during
the filming of the lightning events.

Table I.A: Flight STS-8

Launch Date: 30 August 1983
Filming Date/Time: 4 September 1983, 03:11:32 GMT
Location: Over the Gulf of Mexico:
 27°N latitude, 83°W longitude
Altitude: 222 km
Camera Parameters:
 RCA SIT (Silicon Intensified Target) Video Camera
 Diagonal Field of View: 46° normal, 8° zoom
 Focal Length: 16 mm

Table I.B: Flight STS-9

Launch Date: 28 November 1983
Filming Date/Time: 2 December 1983, 11:38:25 GMT
Location: Over the South Atlantic Ocean:
 33°S latitude, 34°W longitude
Altitude: 249.7 km
Camera Parameters:
 SEPAC SIT Vidicon Camera (low light monochrome camera)
 Horizontal Field of View: 28.7°
 Vertical Field of View: 21.7°
 Focal Length: 25 mm
 Spectral Response: 390-700 nm

Table I.C: Flight STS-41D

Launch Date: 30 August 1984
Filming Date/Time: 1 September 1983, 14:09:35 GMT
Location: Northwest of New Guinea:
 2°S latitude, 150°E longitude
Altitude: 296-331 km (average 313.5 km)
Camera Parameters: SIT Video Camera
 Diagonal Field of View: 51.5° (18 mm focal length)
 7.2° (108 mm focal length)
 Focal Length: 18 mm used in the video
 Video taken from Remote Maneuvering System

Table I.D: Flight STS-51J

Launch Date: 3 October 1985
Filming Date/Time: Classified
Location: Over Typhoon Brenda, near Sri Lanka
Altitude: 487-518 km (average 502 km)
Camera Parameters:
 IT&T Model 4561 Video Camera with an intensified
 Charge Injected Device (CID)
 Horizontal Field of View: 19.96°
 Vertical Field of View: 15.03°
 Focal Length: 25 mm
 Spectral Response: Peaks at 580 - 750 nm
Camera Parameters for Zoom Lens:
 Horizontal Field of View: 3.36°
 Vertical Field of View: 2.53°
 Focal length: 150 mm

lightning, it was also traced.

Figure 1 illustrates the appearance of a lightning flash on the video monitor. The region below the limb of the earth is space. Figure 2 illustrates how the lightning would look when viewed, from the shuttle, by the video camera. Lines AEB, A'E'B', AA', and BB' mark the edge of the field of view of the camera. These lines correspond to those shown in Figure 1. The shaded region represents the earth's surface.

The video tapes were played back on a Panasonic PV-9000 Portable Video Cassette Recorder connected to a Panasonic PV-A860 Programmable Tuner. This particular model was chosen because of the clarity and stability of its still frame mode. The video tapes were viewed in a darkened room. The monitor was set at the same brightness and contrast level for all 323 flashes. Reference marks were placed on the monitor, and traced along with the illumination, to insure proper alignment of successive frames of a flash. The time and frame number were noted on each trace.

Two different geometric analysis schemes were used to analyze the size of an event (see Appendix). The first method was applied when the camera was pointed at nadir, as in the portion of the STS-51J video which was taken with the zoom lense. The second method was used when the camera was pointed away from nadir, and the limb of the earth appeared in the video picture, as in the STS-51J, STS-8, and STS-41D videos. The video from flight STS-9 presents a problem because the limb of the earth does not appear in it, and the camera angle with respect to nadir is unknown. It was assumed that

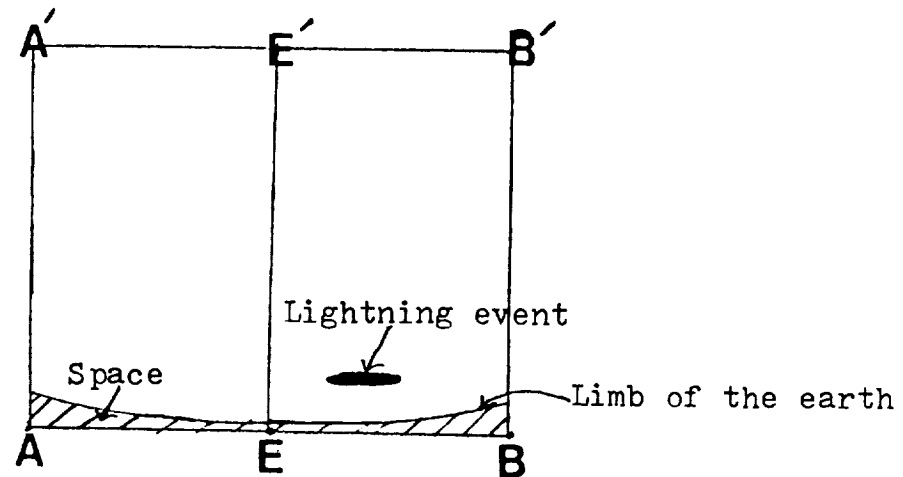


Figure 1: A lightning event, as it appears on the video monitor. The region below the limb of the earth represents space. Lines AEB, A'E'B', AA', and BB' mark the edges of the field of view of the camera.

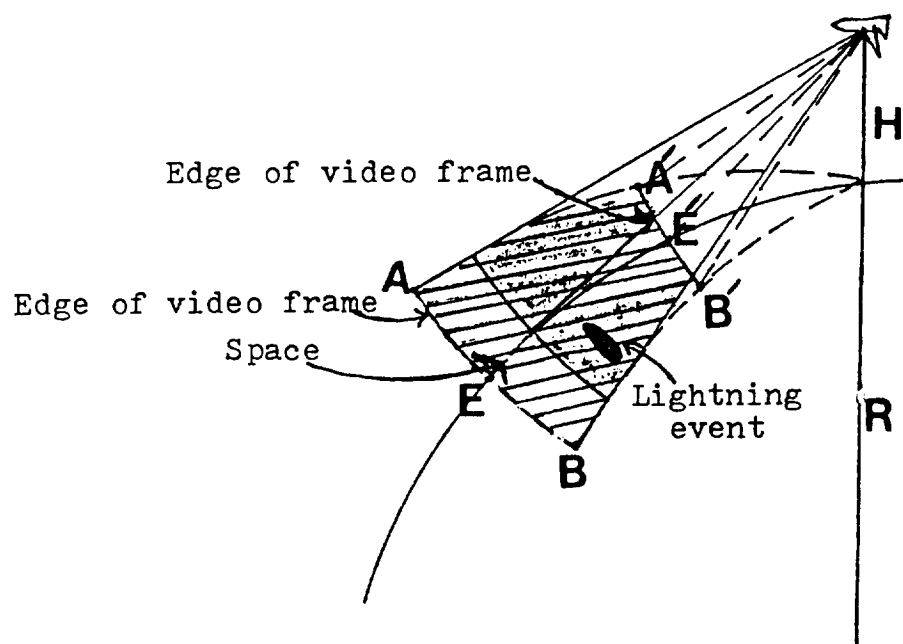


Figure 2: A lightning event, as viewed from the space shuttle. The shaded, diagonally lined region represents the earth's surface. Lines AEB and A'E'B' correspond to lines AEB and A'E'B' in Figure 1.

the camera was directed at nadir. This assumption gave the minimum possible dimensions of the illumination. The dimensions of lightning events from the STS-9 video could be larger by at least a factor of 2, if the camera was tilted such that the limb of the earth was just beyond the viewing area.

In several instances, during the lifetime of a lightning flash, the illumination was so faint, that the borders of the flash could not be distinguished. This occurred when the lightning image was very small, and lasted from one to three successive frames of the video. In the data, these untraceable frames were recorded as not measurable. This was done in order to keep an accurate time duration for each flash.

III. RESULTS

This study addresses several questions. For instance, what are the size and duration characteristics of the lightning events? Do larger flashes also last longer? Do smaller flashes reach their maximum area more quickly than larger flashes? At what point in the flashes lifetime is the maximum area attained?

The results have been divided into seven sections. In section 3.1 the reader gets a taste of what the lightning flashes look like. This section includes photographs of the lightning flashes, as well as the composite traces of several events. Section 3.2 reveals some of the characteristics of these flashes. The average duration, size, and rate of propagation of the illumination, from the initial to the largest dimension of a flash, are given.

The relationships between the maximum area of a flash and its duration, the time that the maximum area occurred, and the percent of the total duration at which the maximum area occurred are shown in section 3.3.

Section 3.4 of the results shows how the area of the flashes changed over their lifetime by presenting plots of the area of a flash versus time. The number of peaks in the area curve per flash, and the time between these peaks are considered. The time to the initial peak versus the time between a minimum and subsequent peak in the area curve, and the change in the area between peaks are also shown.

Sections 3.5 and 3.6 deal with two groups of flashes which exhibited some unique characteristics. Section 3.5 deals with the traits of a group of flashes which had a bright spot, while in section 3.6 the occurrence of simultaneous events is presented.

Section 3.7 again takes a look at the change in the area of a flash over time. In the first part of this section, the area curves of 9 unusually large events, whose maximum area exceeded 12,000 km², are shown. The area curves of flashes from each flight that are more typical in size, duration, and number of peaks in the area curve are also shown, as well as the area curves of some simultaneous events. The second part of section 3.7 investigates the shape of the area curves, and the fact that each of the curves appears to fall into one of five main shape categories.

The term "all flashes" refers to the fact that a specific value, for example the average area, was calculated using data from all 323 lightning events. The same quantity was then calculated for the flashes from each individual flight. In several instances the plot of a given quantity is not shown separately for STS-8 and STS-41D. This is due to the fact that there were a small number of data points for these two flights. These two videos had only 16 and 8 lightning events, respectively. There were 113 events on the STS-9 video, and 186 flashes on the STS-51J video.

1. What do the Flashes Look Like?

On the video tapes the lightning appears as a brightly illuminated region in the cloud system, usually elliptical in shape.

Figures 3A-K show several frames of lightning events that appeared in the STS-9 video. Figure 3A shows the initial development of a v-shaped flash whose dimensions are approximately 9 km x 8 km in the X and Y directions, respectively. By the seventh frame (200 ms later), this flash has expanded to approximately 17 km x 18 km (Figure 3C). It was unfortunate that the flash was partly outside the field of view of the camera at this time. In frame eight (233 ms later) another flash appears (Figure 3D). This event was 25km from the initial flash. In Figure 3G, a hook shape can be seen extending from the base of the initial flash. It is more clearly visible at 566 ms (Figure 3J). In frame 20 (Figure 3K), a third flash appears 15 km to the lower right of the center flash. These lightning events were visible for another 13 video frames (433 ms).

A composite sketch, of the frame by frame traces of the outline of the region which is illuminated by a flash, illustrates the development of a lightning event over time. A composite trace from one of the flashes photographed with the zoom lens on STS-51J is shown in Figure 4. Flash 11, and flashes 77 and 78 of STS-9 are shown in Figures 5A and 5B. The composite traces of the fifteenth flash of STS-8 and the second flash of STS-41D appear in Figures 6A and 6B, respectively. Flashes 6 and 7, 101 through 104, 112 through 114, and 169 through 174, from the STS-51J video, are illustrated by the composite traces in Figures 7A, 7B, 8A, and 8B.

The initial trace of the illuminated region is identified by a 33, because the event appeared 33 ms after the previous frame on which there weren't any flashes. This previous frame, in which

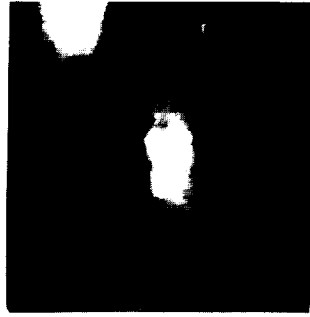
Figure 3: Figures 3A through 3K show frames 1, 3, 7, 8, 10, 11, 13, 14, 15, 17, and 20 of simultaneous lightning events which appeared in the STS-9 video. The frame number is noted, along with the elapsed time in parentheses. In the initial frame (3A), the flash had dimensions of 9 km x 8 km. 233 ms later (3D), a second flash appears 25 km away. In the 20th frame (3K), yet another lightning event appears, 15 km away from the second event. Notice the hook shaped extension on the lower right of the initial event in Figures 3G-K. In Figure 3K, the approximate dimensions of the initial event are 34 km x 22 km. Those of the event in the center are 46 km x 17 km, while those of the the third event are 4.5 km x 4.5 km.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

3A. Fr 1 (33ms)



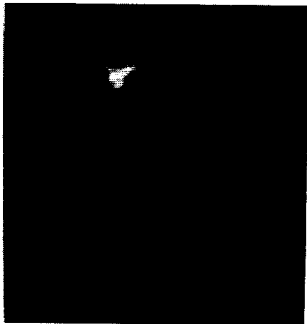
3E. Fr 10 (333ms)



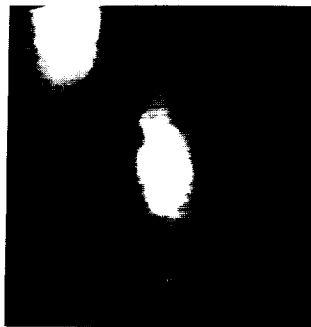
3I. Fr 15 (500ms)



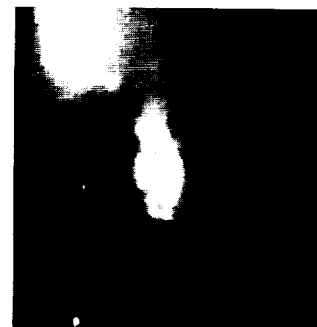
3B. Fr 3 (100ms)



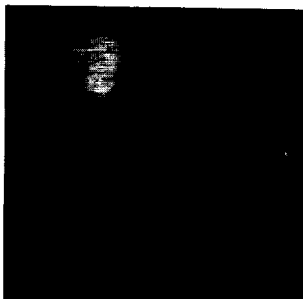
3F. Fr 11 (366ms)



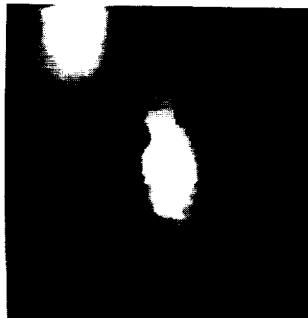
3J. Fr 17 (566ms)



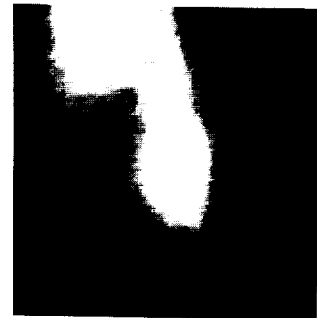
3C. Fr 7 (233ms)



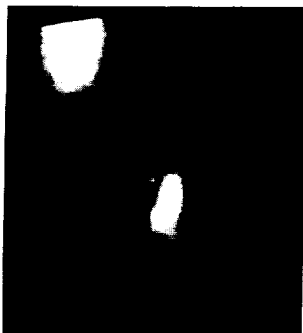
3G. Fr 13 (433ms)



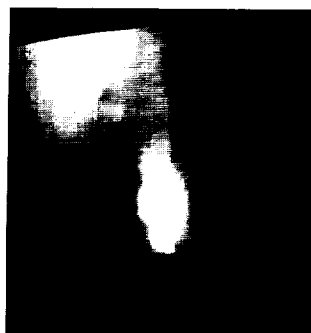
3K. Fr 20 (666ms)



3D. Fr 8 (266ms)



3H. Fr 14 (466ms)



Fr - Video frame
number

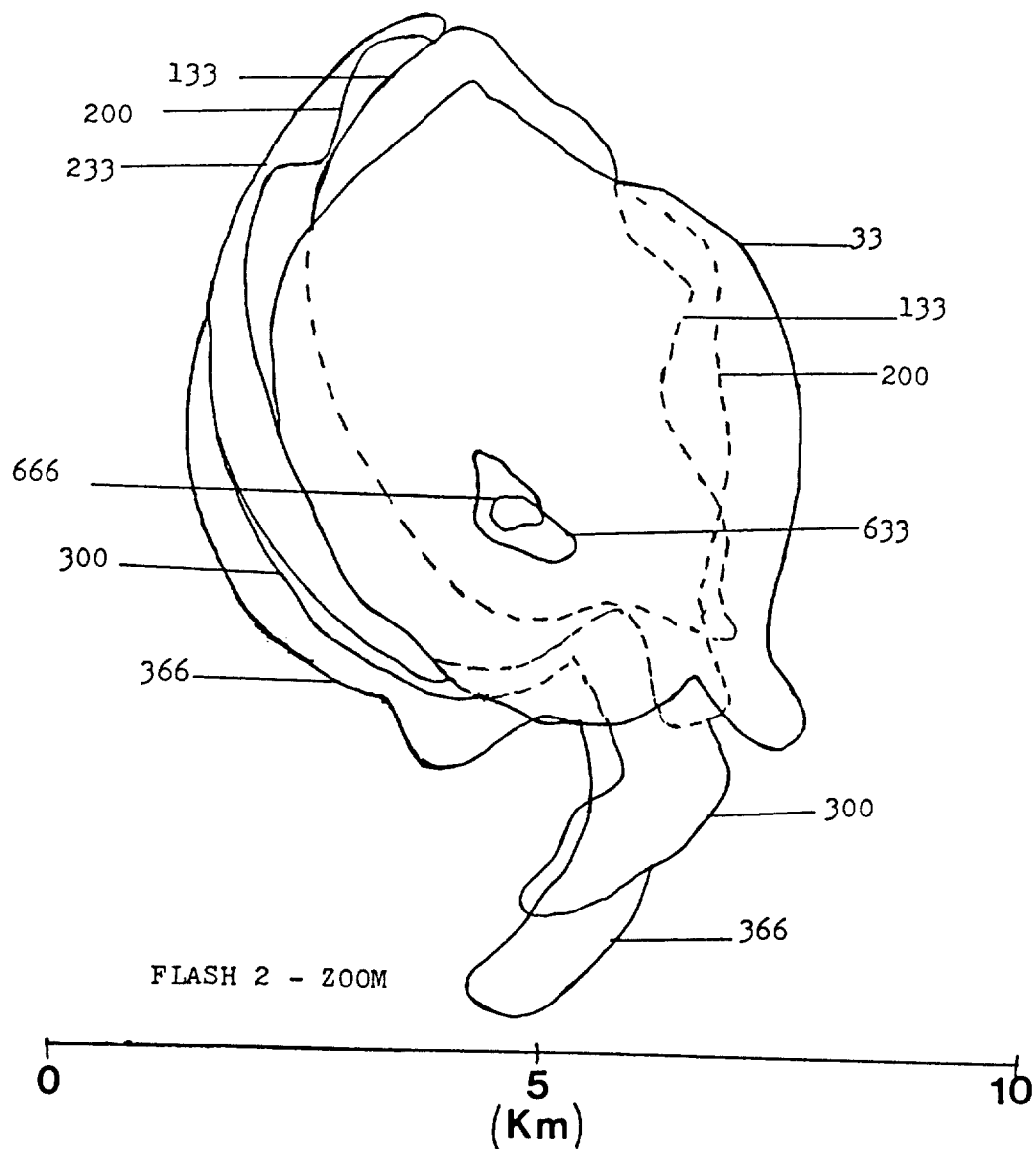
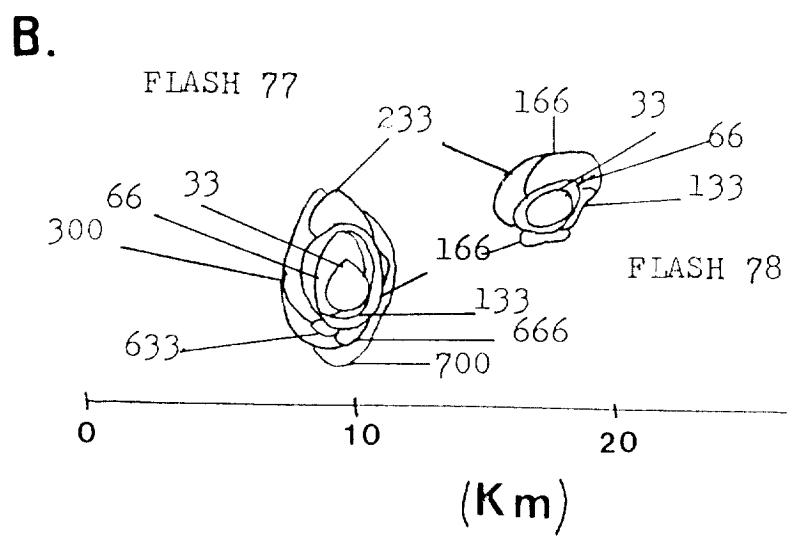
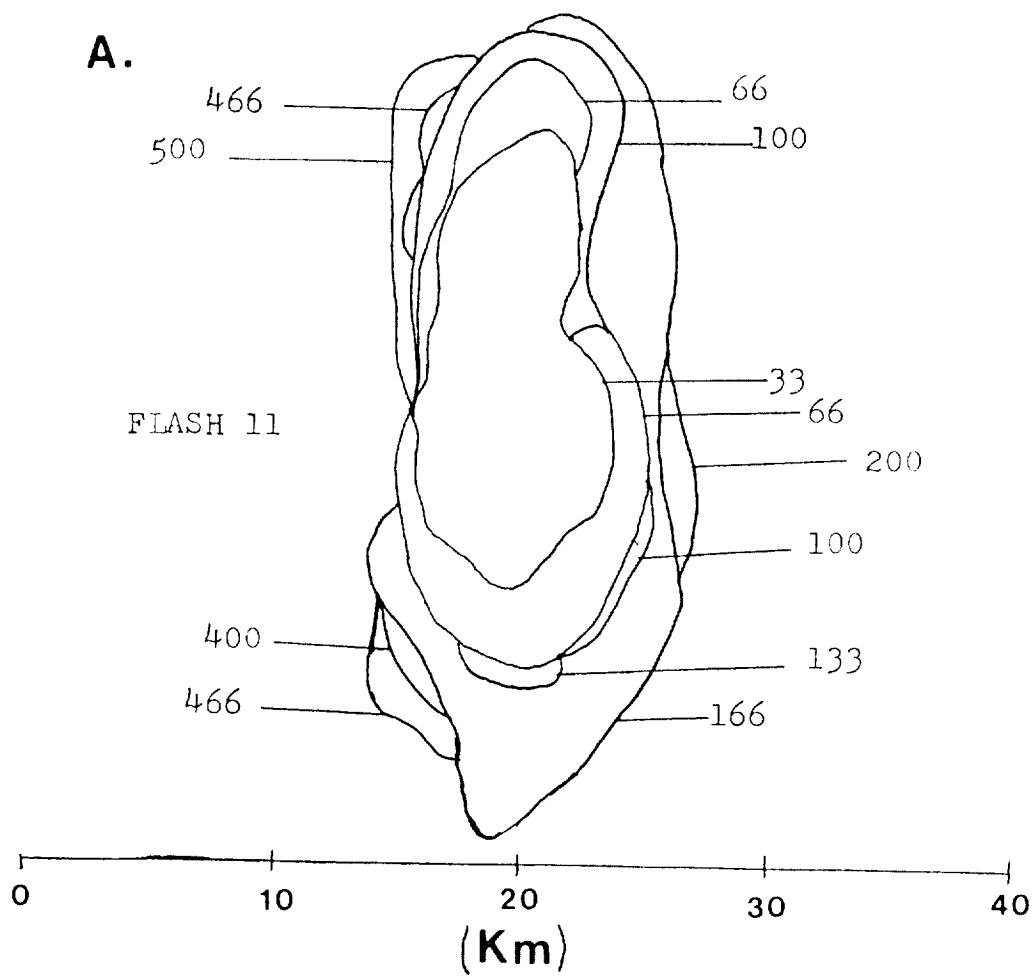
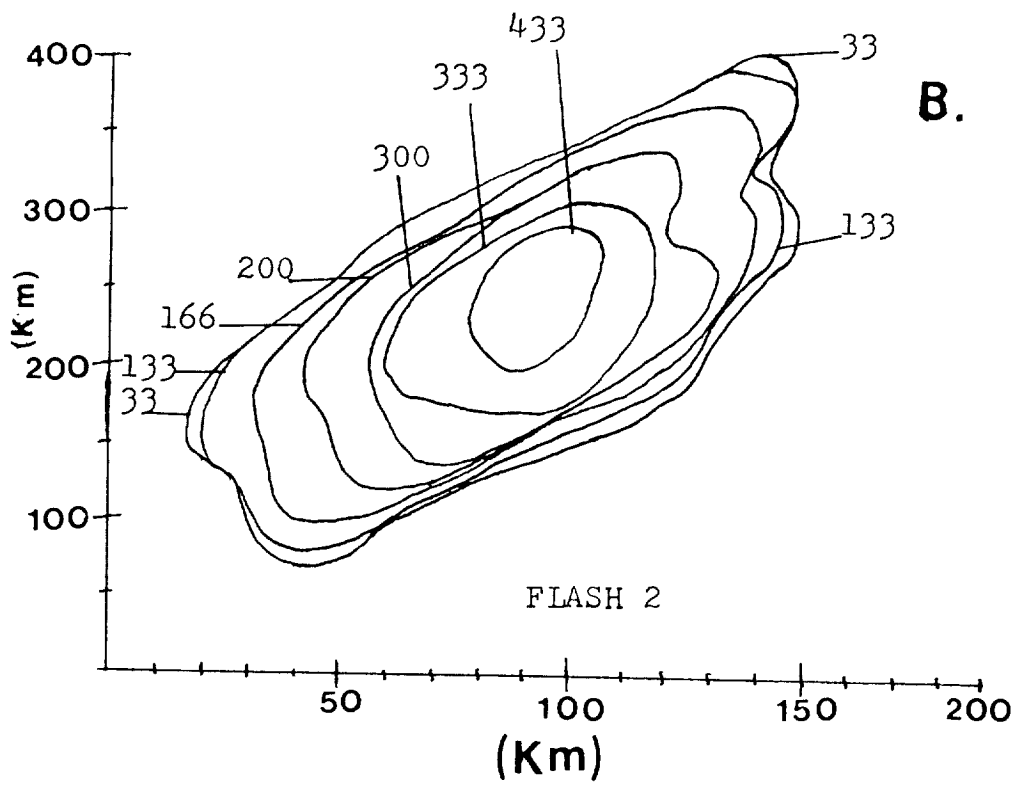
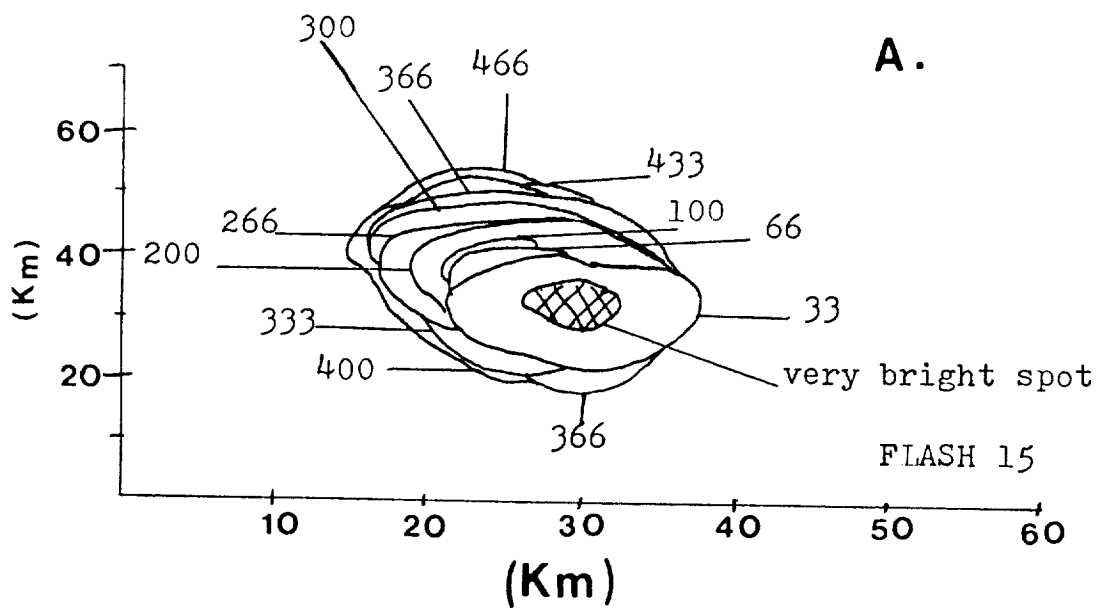


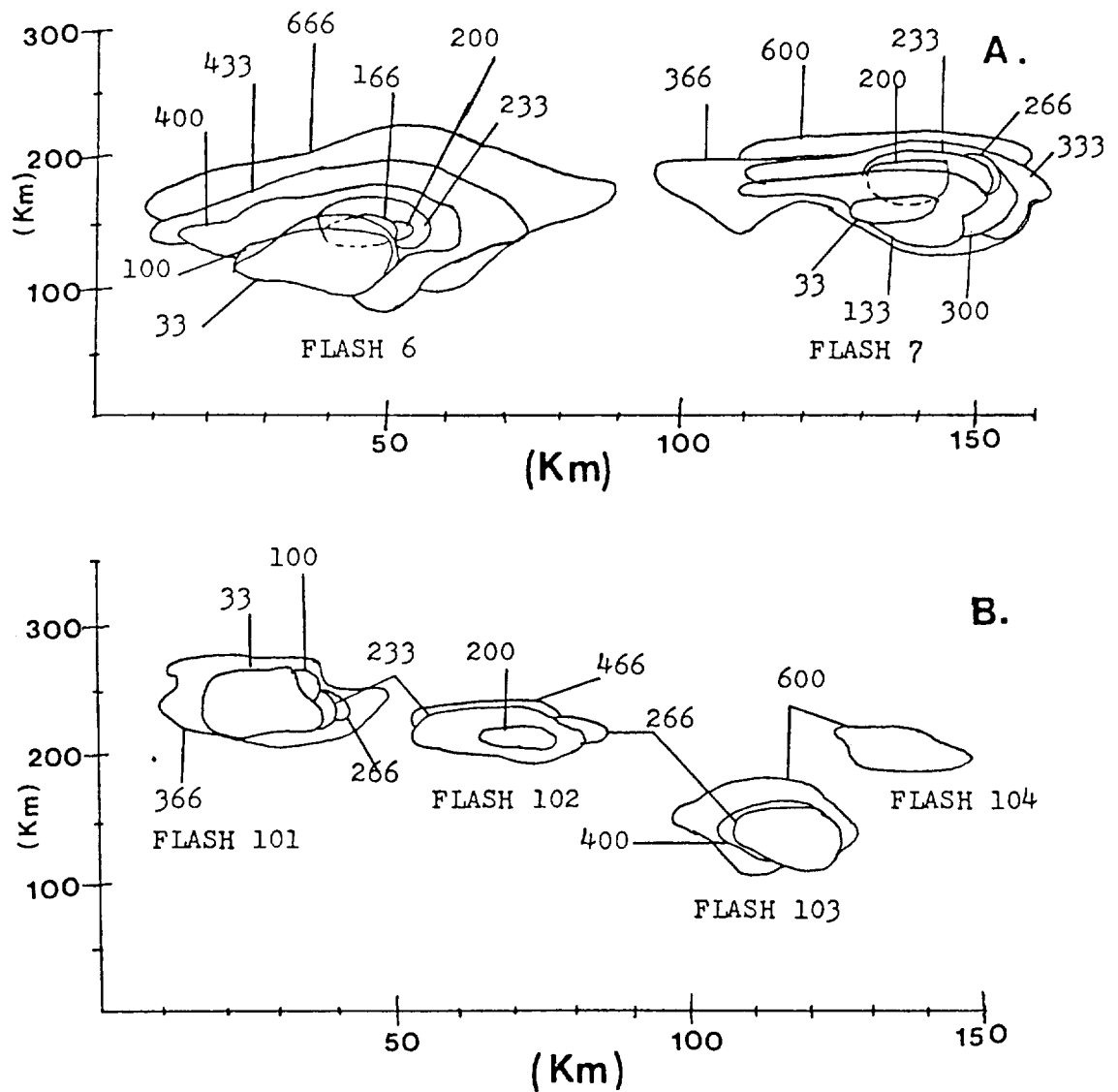
Figure 4: A composite trace of one of the flashes from STS-51J, which was photographed with a 150 mm zoom lens. The initial trace of this event is labeled 33. The subsequent traces are labeled according to when they appeared after frame 0 (the frame preceding frame 33 in which no flash was present).

Figures 5A and B: Figure 5A is a composite trace of flash 11 from STS-9. Contours are labeled as explained in Figure 4. Notice that this event grows in a favored direction. That is, its greatest size increase occurs along an axis from the top to the bottom of the page. Figure 5B is a composite trace of two simultaneous events from STS-9. These two events were approximately 6 km apart when they first appeared.



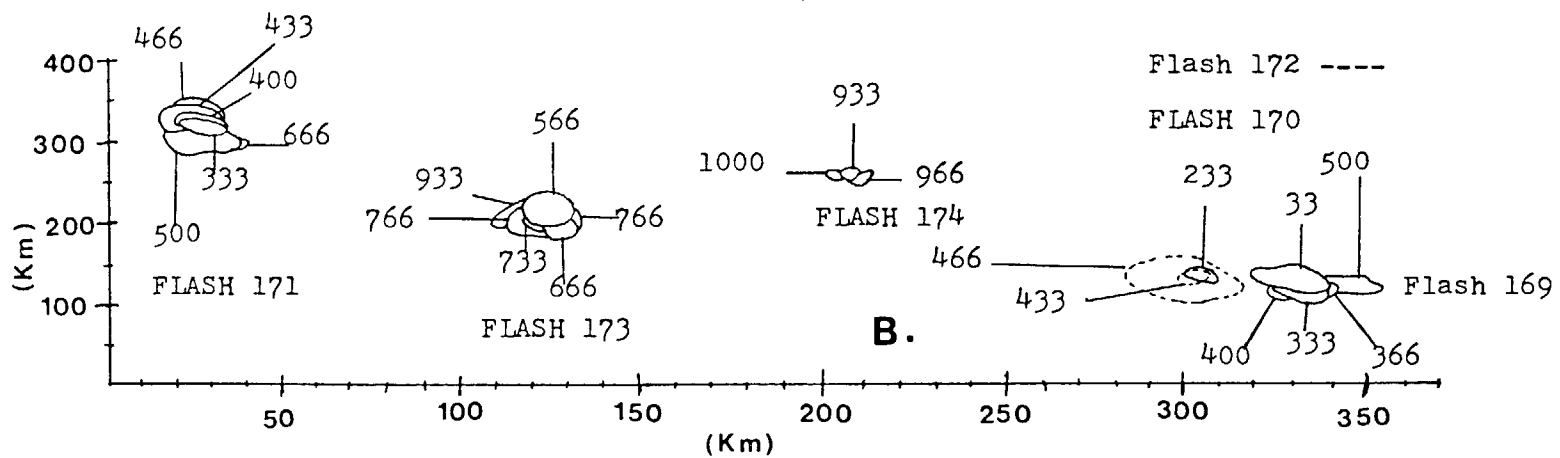
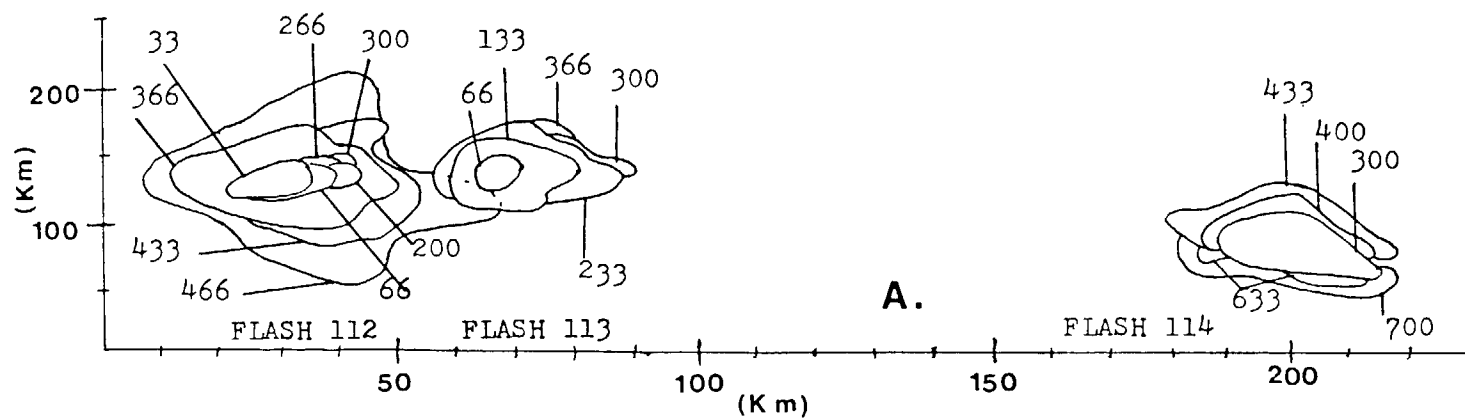
Figures 6A and B: Contours for both A and B are labeled as explained in Figure 4. Figure 6A is a composite trace of flash 15 of STS-8. The hatched region indicates the location of a persistent bright spot which appeared in a small percentage of all 323 events. Figure 6B is a composite trace of flash 2 from STS-41D. Note that the initial frame of flash 2 is also its largest.





Figures 7A and B: Contours for both A and B are labeled as explained in Figure 4. Figure 7A shows the composite traces of two simultaneous events from the STS-51J video. These two events were 80 km apart when they first appeared together. Figure 7B shows a series of simultaneous events, also from the STS-51J video. Events 101, 102, and 103, and events 103 and 104 occurred together.

Figures 8A and B: Contours for both A and B are labeled as explained in Figure 4. Figure 8A is a composite trace of three simultaneous events from the STS-51J video. Flashes 112 and 113, and 113 and 114 were 20 km and 130 km apart, respectively, when they first appeared. Figure 8B is a composite trace of a series of six simultaneous flashes from the STS-51J video, which occurred over a 1066 ms time period. The greatest number of events appearing at any one time in this series of events was four. Note that event 172, represented by the broken line, appeared near the same location as event 170, but 200 ms later.



flashes did not appear, is designated as frame 0. Each successive illuminated area which develops is labeled to show how many milliseconds it appeared after frame 0.

It must be kept in mind that the determination of the boundaries of an illuminated region is somewhat subjective. The difference between the edge of a flash and the surrounding region is not always well defined. There is also some subjectivity involved in the interpretation of the progression of a flash. It is quite possible that the propagation of a flash in a favored direction may be due to the movement of either the camera, or the space shuttle. In the videos from STS-8, STS-41D, and that part of the STS-51J video filmed with the 25 mm lens, the limb of the earth is visible. Therefore, in these videos a movement of the camera or shuttle can be more easily recognized because it would result in a change in the position of the limb of the earth relative to the borders of the video frame.

The size scales that appear on the composite traces in Figures 6 through 8 vary in the X and Y directions. As discussed in the appendix, there is a larger foreshortening of the dimensions of a flash, in the direction perpendicular to the limb of the earth, (in this case the Y direction), than in the dimensions that are parallel to the limb of the earth.

Notice that a tail develops near the lower region of a flash which was photographed with a 150 mm lens on STS-51J (Figure 4). The outward extension of a lightning channel could explain this tail. However, a channel was not visible, and the next two flashes which

occurred 133 ms and 12.8 s after this event also developed a similar tail. It seems more likely, therefore, that this tail is formed from the lightning illuminating a crevice within a cloud, or the edge of the cloud in which it is occurring. The last frame on which this flash appeared is labeled 666. At its largest extent, this flash was approximately 10 km x 6 km.

Flash 11 (Figure 5A) propagates outward in almost all directions. This flash lasted 666 ms and had dimensions of 34 km x 15 km at its largest extent. The traces of two simultaneous flashes appear in Figure 5B. These two flashes began within the same 33ms time interval. Whenever two time coincident flashes appear, the distance between them was measured on the first frame in which they coexisted. These two flashes were separated by 6 km. If a breakdown process started at one location, and then spread to the other, the minimum value for the speed of breakdown between these two flashes would be $1.8 \times 10^5 \text{msec}^{-1}$. Flash 77 lasted 933 ms while flash 78 lasted 233 ms.

The location of a persistent bright spot which appeared within the region illuminated by flash 15 of STS-8, is noted on the composite trace of this flash (Figure 6A). At its largest extent, flash 15 had dimensions of approximately 40 km x 25 km. The total duration of this flash was 600 ms. The location of the limb of the earth was relatively constant throughout the lifetime of this lightning event.

The composite trace of flash 2 of STS-41D shows the progression of a flash whose initial area was also its largest (Figure

6B). In this case, the subsequent frames show the decline of the illuminated region over time. This flash lasted 466 ms. In the initial frame that this flash appeared, it had dimensions of 200 km x 130 km.

Flashes 6 and 7 of STS-51J appeared at the same time (Figure 7A). They were 80 km apart on the initial video frame in which they first appeared together. Flash 6 had a duration of 866 ms, while flash 7 lasted 633 ms. The limb of the earth moved upward during the lifetime of these flashes. Therefore it is likely that the upward shift of the illuminated region was at least partly due to movement of the video camera and/or the space shuttle. Flash 6 was 150 km x 80 km at its maximum extent, and flash 7 reached dimensions of 95 km x 70 km. If a breakdown process spread from one of these flashes to the other, the minimum speed of propagation would be $2.4 \times 10^6 \text{ msec}^{-1}$. This is much larger than the 10^5 msec^{-1} rate of growth exhibited by most of the flashes in this study.

Four flashes which occurred throughout a 1000 ms time period are shown in Figure 7B. Flashes 101, 102, and 103 initially appeared in the same video frame. Flash 104 appeared with flash 103 at a later time. Flash 101 lasted 500 ms. Flash 102 appeared 166 ms after flash 101, and had a duration of 366 ms. Flash 103 began 233 ms after flash 101, and lasted 766 ms. Flash 104 appeared 566 ms after flash 101, and lasted for 133 ms. The distances between flashes 101 and 102, 102 and 103, and 103 and 104, were approximately 35 km, 60 km, and 50 km, respectively. If some type of breakdown process did exist between these three flash

pairs, the minimum rate of propagation to connect them would be on the order of 10^5 msec^{-1} .

Flash 112 and 113 of STS-51J were 20 km apart (Figure 8A). Flash 113 appeared 33 ms after flash 112, and continued for another 366 ms. Located 130 km from flash 113, flash 114 began 266 ms after flash 112 and continued for another 433 ms. At their largest extent, flashes 112, 113, and 114 had approximate dimensions of 180 km x 60 km, 80 km x 40 km, and 70 km x 40 km, respectively. If a breakdown process was connecting flash 112 to 113, and flash 113 to 114, the respective minimum speeds would be $6 \times 10^5 \text{ msec}^{-1}$ and $5.5 \times 10^5 \text{ msec}^{-1}$. There was a change in the position of the limb of the earth around 200 ms and again near 600 ms. This change is reflected in the shift in the position of flashes 112 and 114 at these times.

The composite traces for a series of six simultaneous lightning events appears in Figure 8B. Flash 170 appeared 200 ms after flash 169. Both of these flashes reached their largest dimensions on their initial frame. These two flashes were approximately 15 km apart. Flash 171 appeared 300 ms after flash 169, and was located 350 km from it. Flash 172 began 400 ms after flash 169. It appeared in almost the same location as flash 170. It was 20 km away from flash 169. Flashes 173 and 174 began 533 ms and 900 ms, respectively, after the first flash of this series. Flash 173 was 80 km from flash 171. Flashes 173 and 174 are 80 km apart. If a breakdown process existed between flashes 169 and 170, 169 and 172, 171 and 173, and flashes 173 and 174, it would have to propagate at a minimum rate

on the order of 10^5 msec^{-1} . However, if the same type of process occurred between flashes 169 and 171, it would have to travel at a minimum speed of $1.2 \times 10^6 \text{ msec}^{-1}$. The total duration of the time period in which these six flashes were visible was 1066 ms. The greatest number of flashes appearing at a given time in this series of events was four.

2. Characteristics of the Lightning Flashes.

a) Duration

A summary of the duration of all 323 flashes is shown in Figure 9. The average flash duration was 400 ms. The longest flash lasted 1833 ms, and the shortest event lasted only one video frame. Ninety-three percent of all flashes lasted less than 800 ms (Figure 10). Of the 22 flashes which lasted longer than 800 ms, 16 appeared in the STS-51J video which was filmed over typhoon Brenda. Four of the flashes with a long duration appeared in the STS-9 video which was filmed over the south Atlantic. The remaining two appeared in the STS-8 video which was filmed over the Gulf of Mexico. The average duration of the flashes whose lifetime lasted less than 800 ms was 357 ms, while that for flashes whose lifetime was greater than or equal to 800 ms was 998 ms.

The duration of the lightning is shown separately for each flight in Figures 11A through C. The duration of events in the STS-41D and STS-8 videos have been grouped together for convenience because of the small number of flashes appearing in these two videos. The average duration of the flashes from STS-8

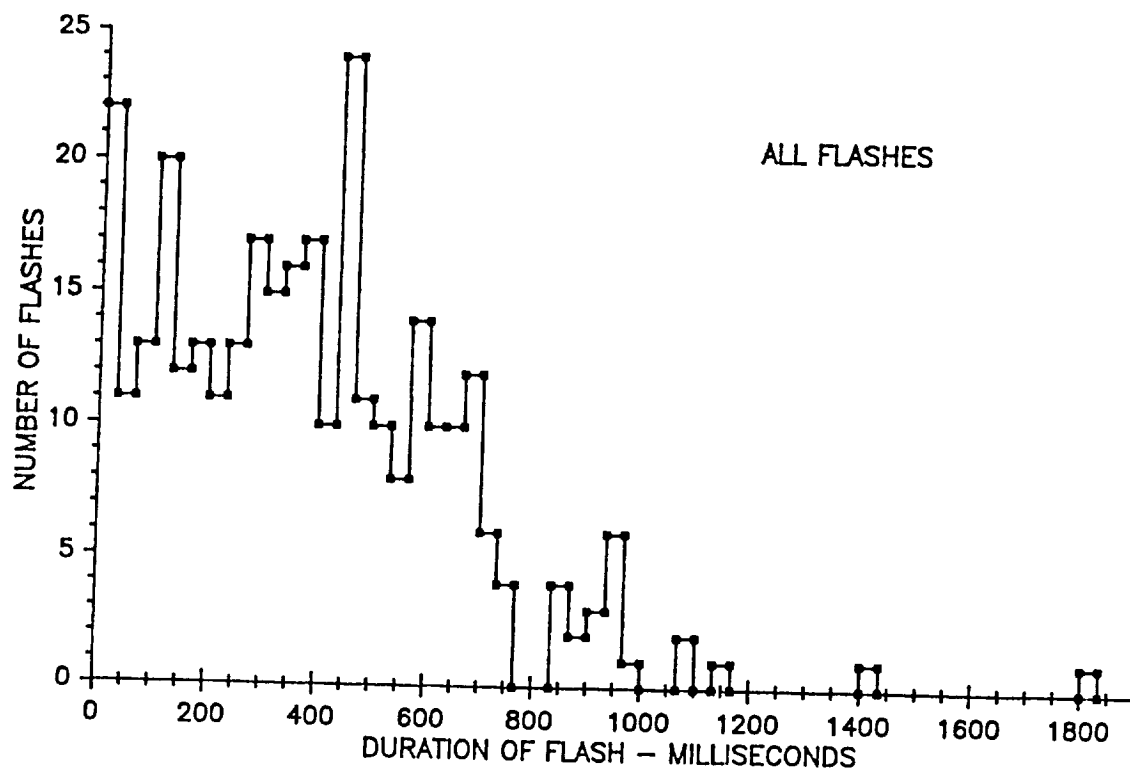


Figure 9: The duration of a flash (in 33.3 ms time intervals) versus the number of flashes with a given duration, for all 323 events. The average duration of all events was 400 ms.

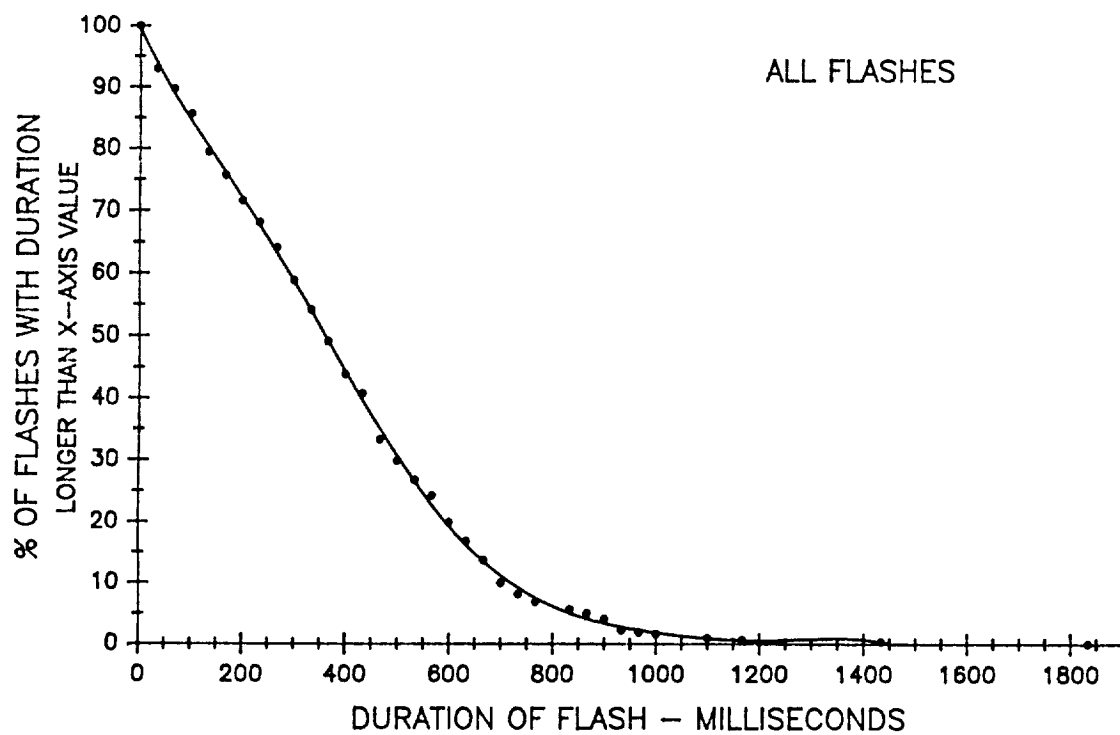
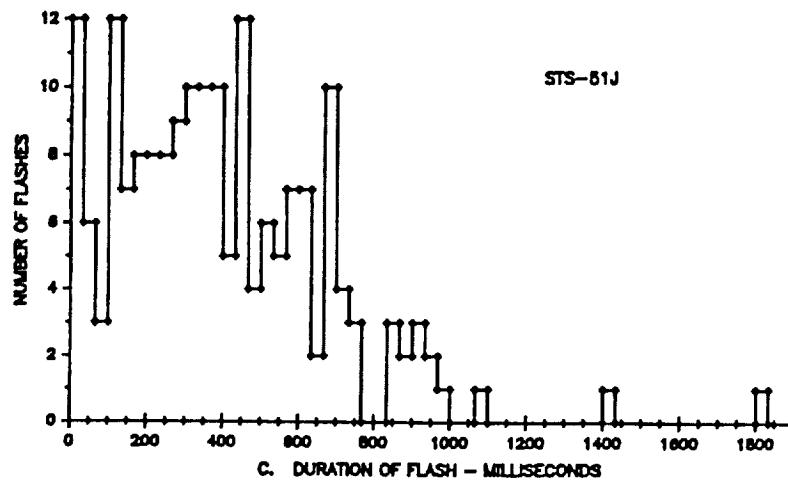
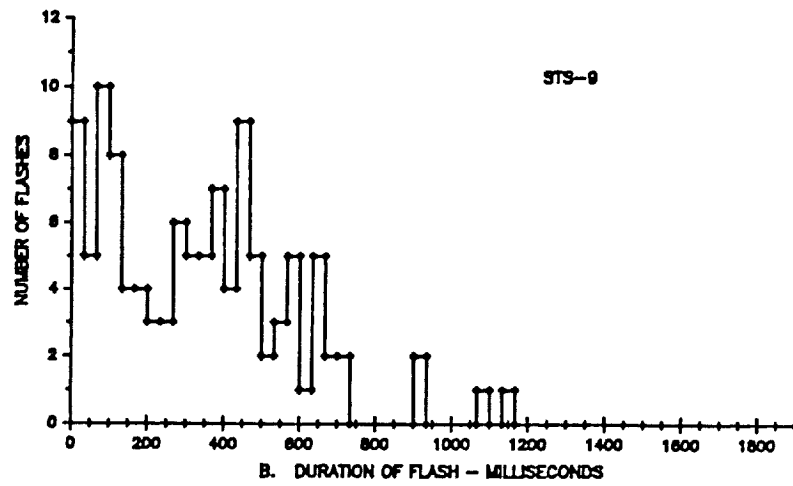
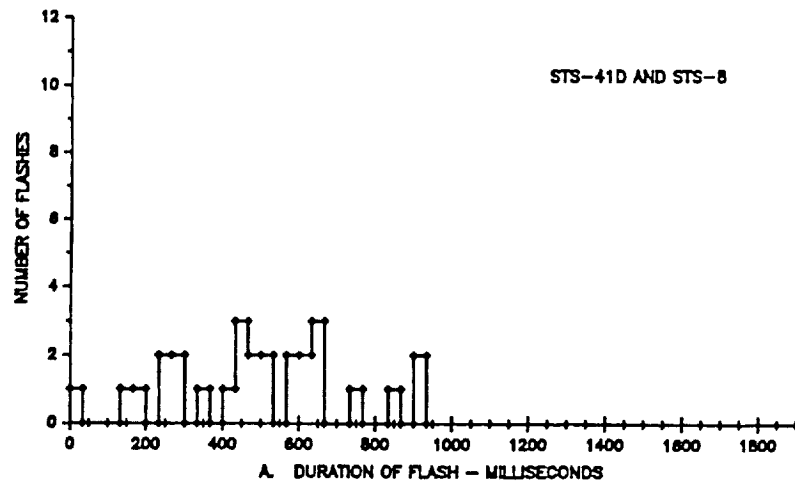


Figure 10: The duration of a lightning event (in milliseconds) versus the percent of flashes whose lifetime was longer than the duration of a given event, for all 323 flashes. The curve was calculated by a 9th order regression.

Figures 11A - C: The duration of a flash (in 33.3 ms time intervals) versus the number of flashes with a given duration, for STS-8 and STS-41D, STS-9, and STS-51J (Figures 11A, 11B, and 11C, respectively). The events of STS-8 and STS-41D were combined because of the small number of events in each data set. The average flash duration for STS-8, STS-41D, STS-9, and STS-51J was 587 ms, 312 ms, 350 ms, and 416 ms, respectively.



and STS-41D was 587 ms and 312 ms, respectively. The average duration of the flashes from STS-9 was 350 ms. Those of STS-51J had an average duration of 416 ms. More than 90% of the events from STS-9 and STS-51J lasted less than 800 ms. 87% and 100% of the lightning events from STS-8 and STS-41D, respectively, had durations less than 800 ms (Figures 12A - C).

b) Dimensions of the major and minor axes.

As previously mentioned, the lightning flashes usually appeared elliptical in shape. The major and minor axis of each flash was determined, and then the area of the flash was estimated by using the equation for the area of an ellipse. A summary of the average values and range of the initial and largest dimensions of the major and minor axes, and the average values of the initial and largest area of a flash are shown in Tables II and III. Table II also shows the length of each video tape and the number of lightning events appearing on each tape.

On average, the initial dimensions of the major and minor axes for all flashes were 20 km and 11 km, respectively. The average maximum dimensions of the major and minor axes for all flashes were 50 km and 25 km, respectively. The lightning appearing in the STS-41D video had the greatest average values of the initial and largest dimensions of the major and minor axes when compared to the other videos. The average initial and largest dimensions of the major and minor axes measured from the lightning on the STS-9 video were an order of magnitude smaller than for the same values on the other three flights. This may be a result of the assumption that the

Figures 12A - C: The duration of a lightning event (in milliseconds) versus the percent of flashes whose lifetime was longer than the duration of a given event, for the flashes of STS-8 and STS-41D, STS-9, and STS-51J (Figures 12A, 12B, and 12C, respectively). The curves for STS-8 and STS-41D, STS-9, and STS-51J were calculated by 5th order, 7th order, and 10th order linear regressions, respectively.

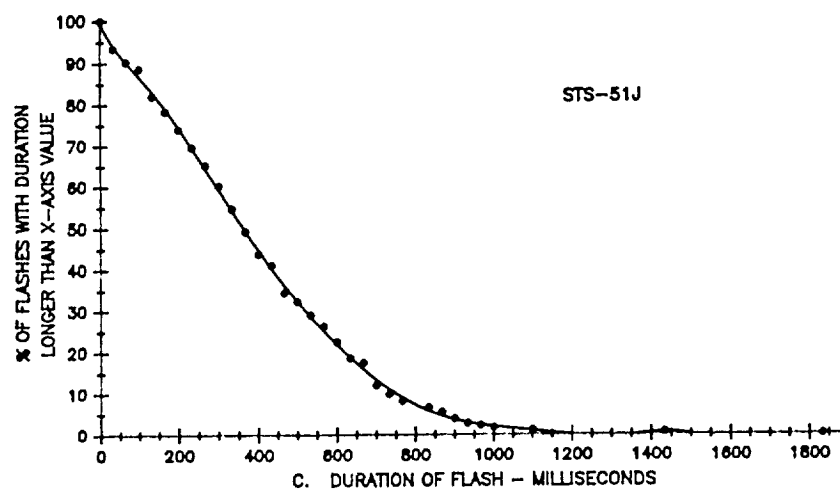
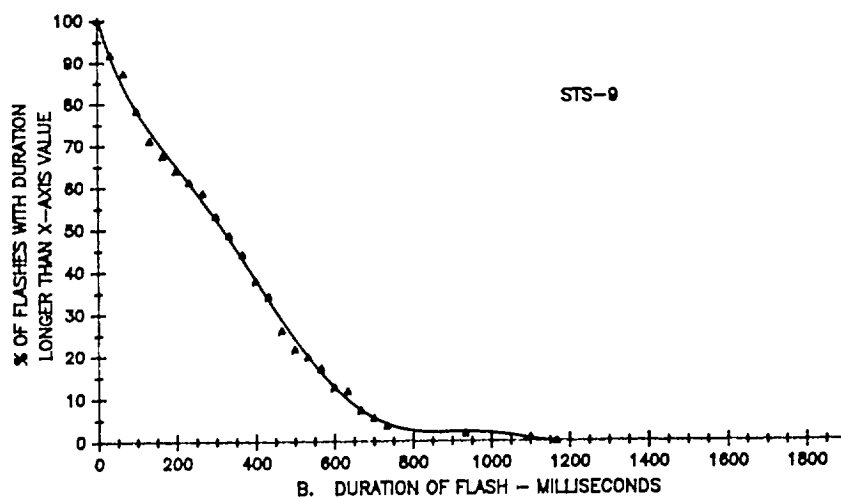
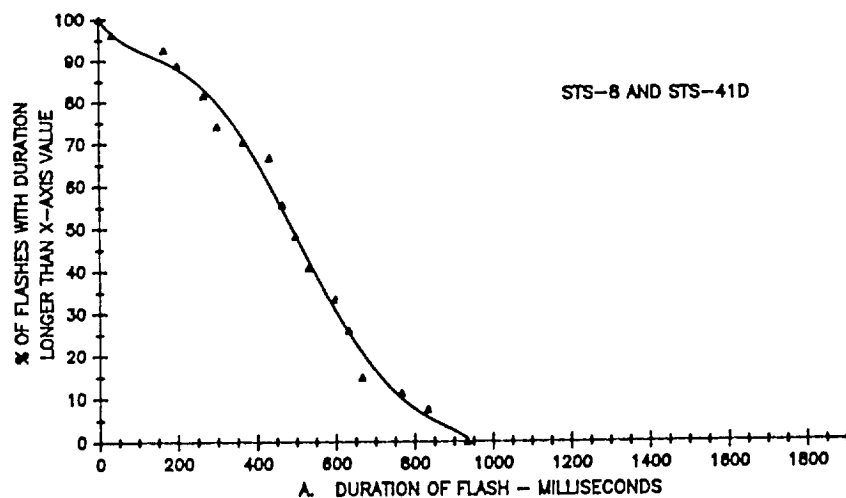


Table II: Initial major and minor axes dimensions of lightning for all events and for those of each flight.

Flight	Number of flashes	Length of video (sec.)	Average initial dimension (km)		Range of initial dimension (km)	
			major axis	minor axis	major axis	minor axis
STS-8	16	61	29	20	11-98	6-52
STS-9	113	192	4	3	1-22	.5-18
STS-41D	8	170	52	40	4-137	2-123
STS- 51J	186	210	27	15	2-102	2-58
All Flashes	323	632	20	11	1-137	.5-123

Table III: Average largest major and minor axes dimensions, and average initial and maximum area for all flashes and for each flight.

Flight	Average largest dimension (km)		Range of largest dimension (km)		Average initial area (km ²)	Average largest area (km ²)	Average ratio of (A_1/A_i)*
	major axis	minor axis	major axis	minor axis			
STS-8	70	50	20-170	8-120	700	3890	6
STS-9	10	6	1-45	.5-35	20	88	9
STS-41D	90	65	14-200	7-130	3040	7420	2
STS-51J	70	35	8-440	5-130	460	2640	8
All Flashes	50	25	1-440	.5-130	380	1870	8

* A_1 is the area of the largest region illuminated by a flash, and A_i is the area of the region initially illuminated by the same lightning event.

camera was pointed straight down during the filming of the video.

Twenty-two of the 323 flashes that were measured were partially out of the field of view for part or all of their duration. Only two of these flashes were not partially beyond the field of view at the time that the lightning reached its maximum dimensions. These twenty-two flashes were still included in the calculations of the average values of the major and minor axes, and area. If this group of lightning events had been ignored, it would have resulted in average values of the major and minor axes, which were 8% and 19% smaller for the STS-41D and STS-9 videos, respectively, and 0.3% and 3% larger for the flashes of STS-51J, and all flashes, respectively.

c) The area of the region illuminated by the flashes.

The average value of the area of the initial frame of a lightning event, for all events, was 380 km^2 . The average of the largest area attained in each flash was 1870 km^2 (Table III). The area of the lightning ranged from approximately 0.5 km^2 on the STS-9 video to $36,900 \text{ km}^2$ on the STS-51J video. The flashes of STS-41D had the largest average maximum and initial areas. However, the initial and maximum areas of only eight events were averaged to get these STS-41D values.

In total, there were nine unusually large flashes. The three very large flashes that appeared in the STS-41D video had maximum areas between $13,000 \text{ km}^2$ and $20,500 \text{ km}^2$. The two which appeared on the STS-8 video had approximate areas of $12,700 \text{ km}^2$ and $12,200 \text{ km}^2$. The four very large flashes that appeared on the STS-51J

video had areas between 18,500 km² and 36,900 km².

On average, the ratio of the largest area to the initial area of a flash was 8:1. The value of this ratio ranged from 1:1, to 255:1. It is interesting that the group of flashes with the largest average area (STS-41D events), had the smallest ratio of maximum to initial area.

d) The rate of growth of the lightning.

The average rate of propagation of the illumination from the initial video frame to the time at which the flash reached its largest extent was calculated for both the major and minor axes. The rate of growth was found by dividing the change in the dimension of an axis, from its initial to its largest extent, by the time it took for that change to occur. If the first frame was also the time when the flash was largest, the initial frame was assumed to occur at a time of 0 ms. This means the largest dimensions of the flash would occur at 33.3 ms. The average rate of growth for all flashes, along the major and minor axes of the elliptically shaped illumination, was $3.5 \times 10^5 \text{ msec}^{-1}$ and $1.8 \times 10^5 \text{ msec}^{-1}$, respectively (Table IV). A rate of growth of 10^6 msec^{-1} occurred in thirty-seven lightning events. These events were found among the flashes of STS-51J, STS-41D and STS-8. Thirty-three lightning events from STS-51J exhibited the 10^6 msec^{-1} rate of growth from the initial to the largest dimension, along the major axis. Twenty-six of these thirty-three events reached their largest dimension on the first frame in which they appeared. Nine of the twenty-six also exhibited this rate of growth along the minor axis. In the STS-41D video, one occurrence of the

Table IV: Average rate of growth from initial to largest major and minor axes dimensions for all flashes and for each flight.

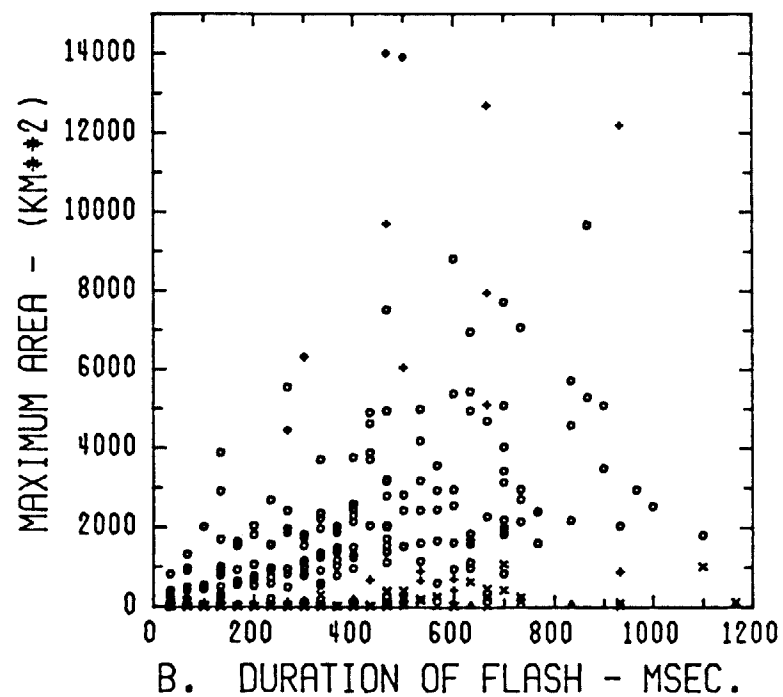
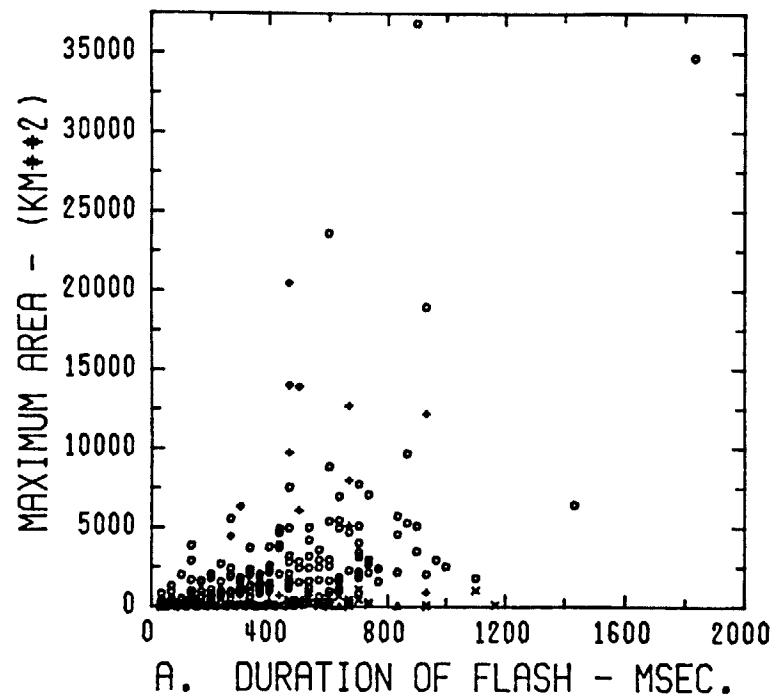
Flight	Average rate of growth from initial to largest dimension ($\times 10^5$ msec. ⁻¹)		Range of the rate of growth from initial to largest dimension ($\times 10^5$ msec. ⁻¹)	
	major axis	minor axis	major axis	minor axis
STS-8	4.2	2.0	0.1-45.0	0.02-15.4
STS-9	0.6	0.3	0.03 - 5.6	0.02 - 2.6
STS-41D	10.8	8.4	0.7-59.1	0.3-39.5
STS-51J	4.8	2.3	0.02-34.6	0.02-21.0
All Flashes	3.5	1.8	0.02-59.1	0.02-39.5

10^6 msec^{-1} rate of growth in the major axis dimension, and one of three occurrences in the minor axis dimension involved a flash whose initial dimension was also its largest. This same growth rate was found in one flash from STS-8 and occurred along both the major and minor axis. Again, this rate of growth was found in a flash which attained its largest dimensions when it first appeared. The flashes of STS-9, which had the smallest average dimensions, also exhibited the smallest rates of growth from the initial to the largest extent of the flash.

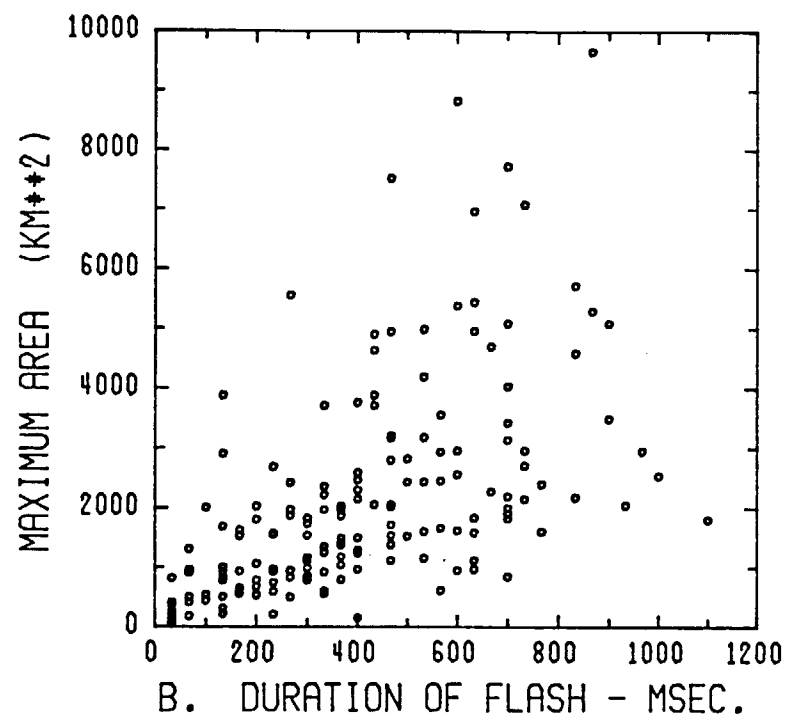
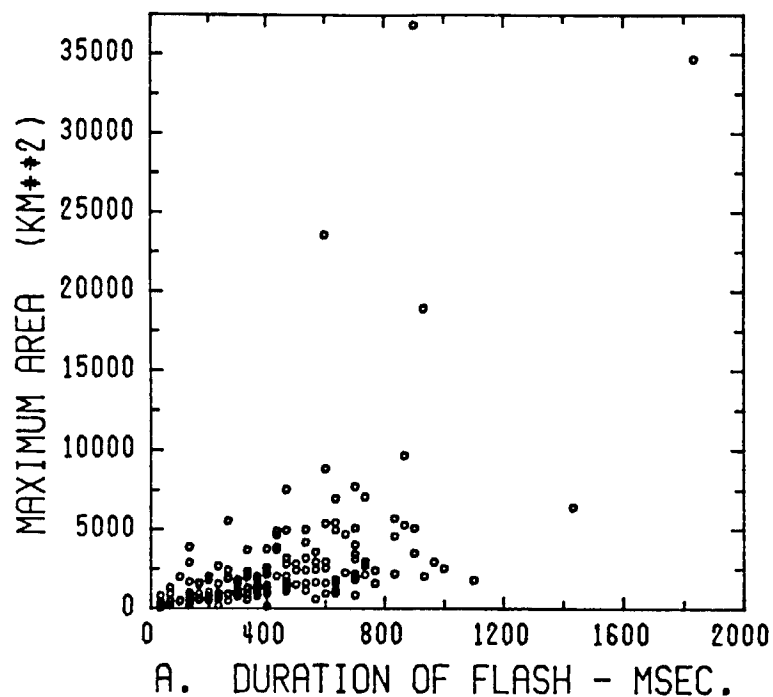
3. The Maximum Area of an Event versus its Duration, the Time that the Maximum Area Occurred, and the Percent of the Total Lifetime of a Flash that Passed when the Maximum Area Occurred.

a) Maximum area versus the duration of a flash.

A scatter plot of the maximum area of each flash versus the duration of the flash for all flashes is shown in Figure 13A. An enlargement of the lower left corner of Figure 13A is shown in Figure 13B, in which the upper time and area values are 1200 ms and 15000 km^2 , respectively. Ninety percent of the flashes had a maximum area that was less than or equal to 5000 km^2 , and a duration of 1200 ms or less. The general trend of the data indicates that as the duration of the flashes increased, the maximum area attained by them also increased. The average maximum area for all flashes with a duration greater than or equal to 800 ms was approximately 7,100 km^2 , while that of flashes with a duration less than 800 ms was approximately 1250 km^2 .



Figures 13A and B: Figure 13A shows the duration of a flash (ms) versus the maximum area attained by that event (km^2), for all events. Figure 13B is an enlargement of the region in 13A which is bounded by 1200 ms and 15000 km^2 . STS-8 events (+), STS-9 events (x), STS-41D events (\diamond), STS-51J events (o), STS-51J with zoom lens (STS-51Jz) (Δ).

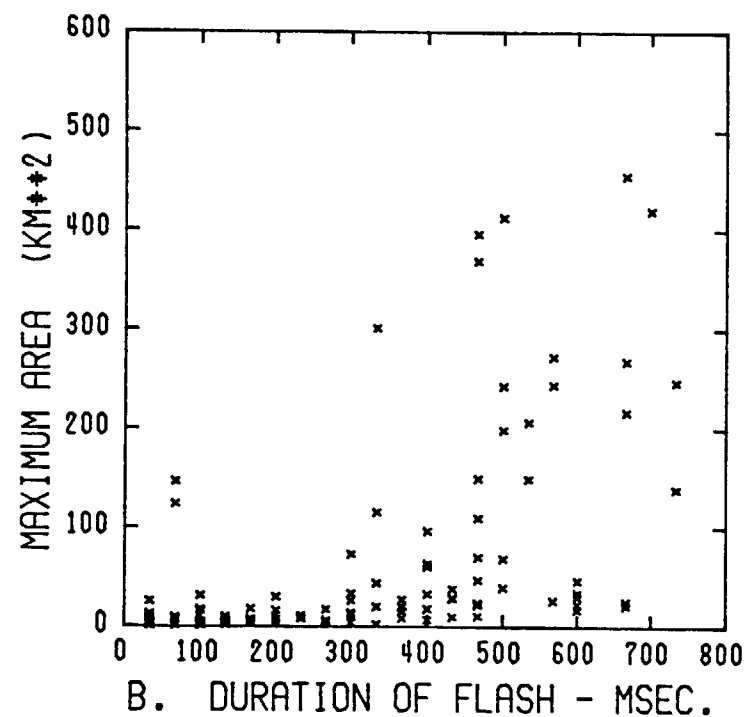
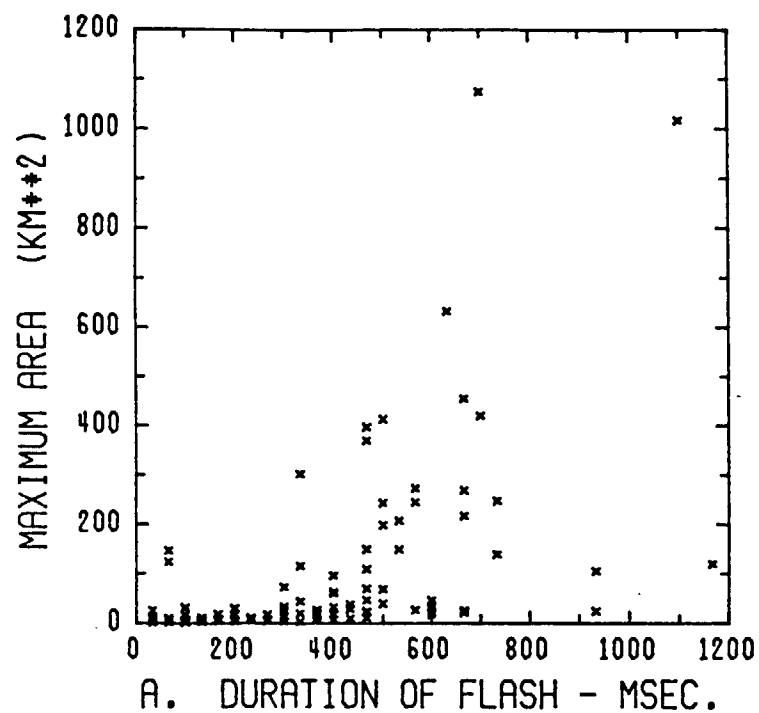


Figures 14A and B: Figure 14A shows the duration of a flash (ms) versus the maximum area attained by that event (km^2), for the events of STS-51J. Figure 14B is an enlargement of the region in 14A which is bounded by 1200 ms and 10000 km^2 .

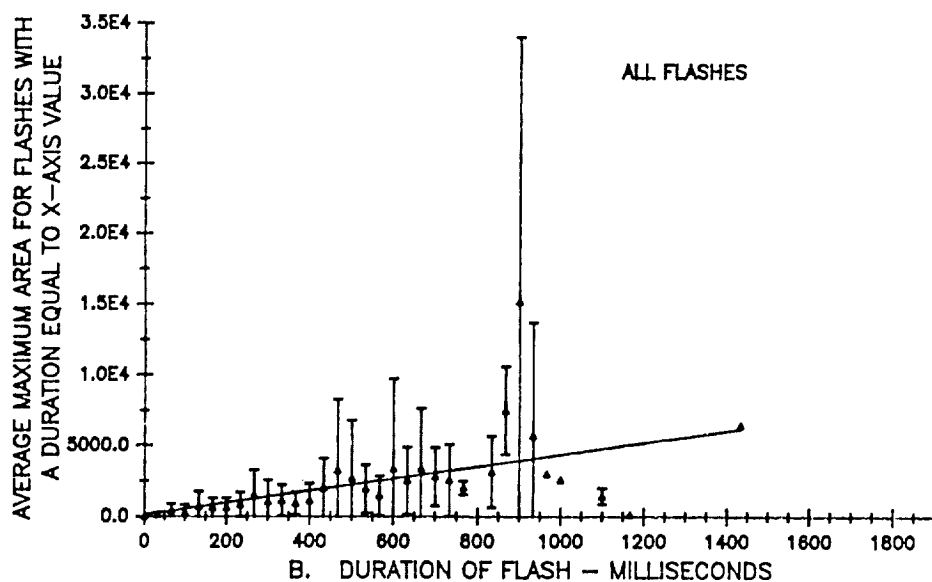
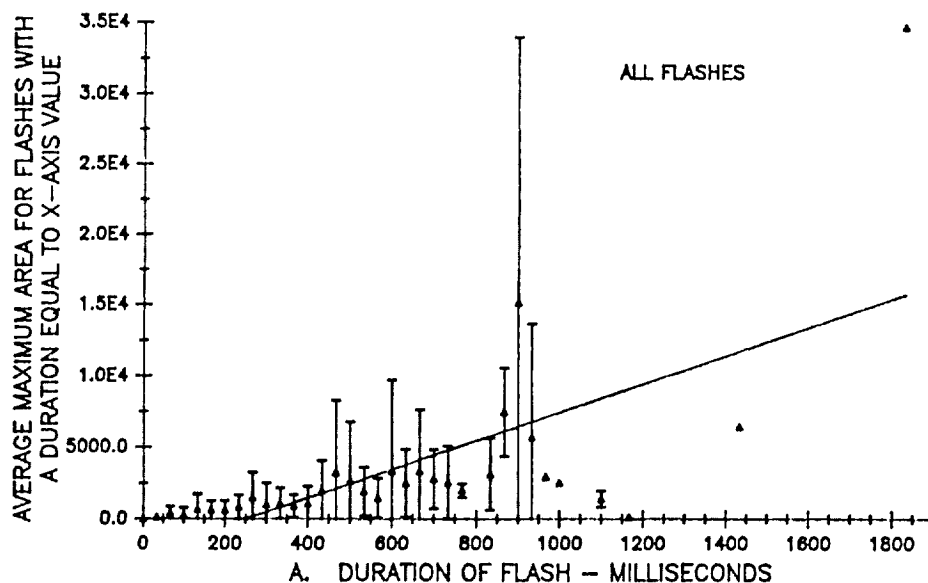
The same type of scatter plot was made for only those flashes that appeared in the STS-51J video (Figures 14A and B). These plots indicate that this group of flashes follows the same general trend of increasing maximum area with increasing duration that appeared in the two previous figures. Again, approximately 90% of the data falls at or below the bounds of 5000 km² and 1200 ms.

Figures 15A and B show the same type of plot for the flashes appearing in the STS-9 video. Initially, as the duration of the flash increases, the maximum area increases rather slowly. After 400 ms, the maximum area increases more rapidly. Approximately 90% of the flashes in this video had durations less than 800 ms and maximum areas less than or equal to 400 km². Separate plots for flashes in the STS-8 and STS-41D videos are not shown because of the small number of events in these two videos.

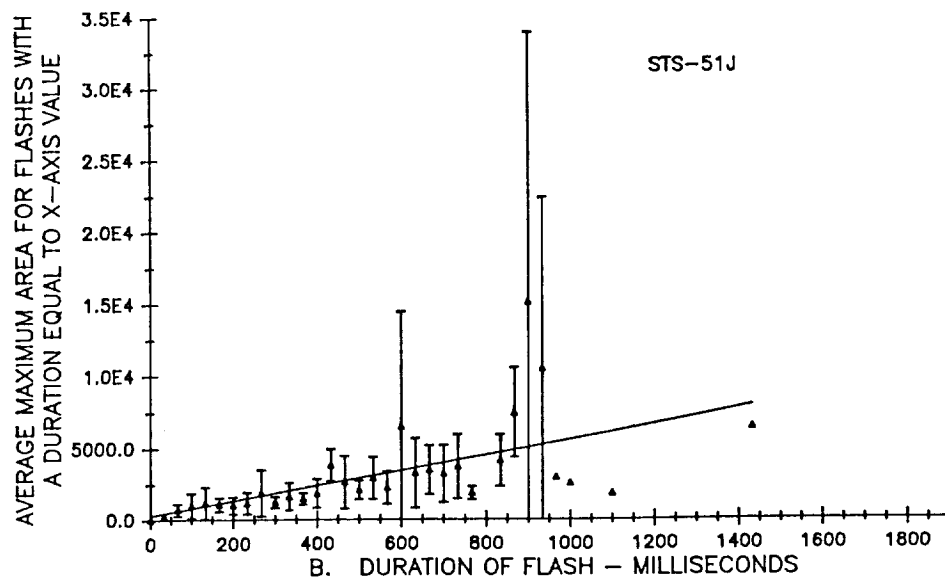
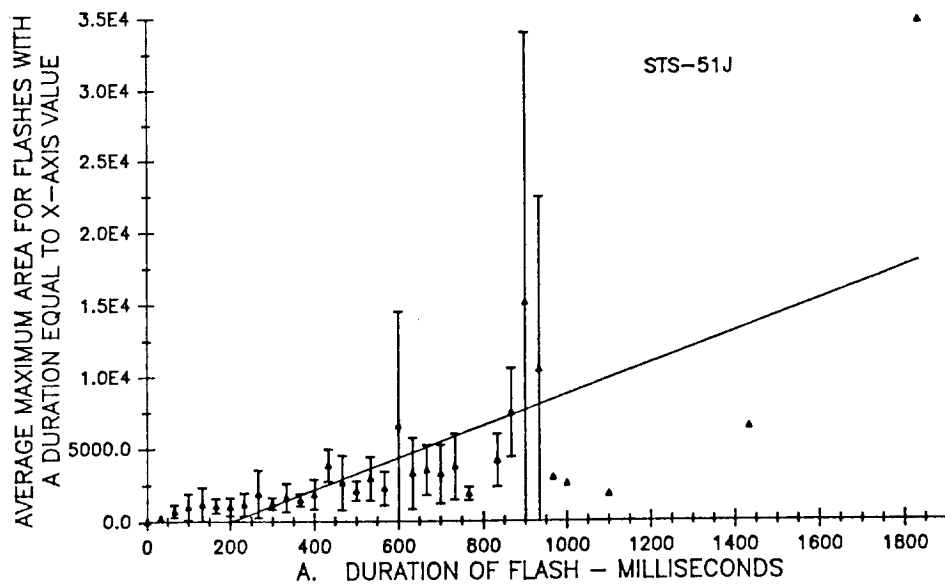
The maximum area values, which are plotted in Figures 13-15, were averaged for each 33 ms interval. The average of the maximum area versus the duration was then plotted (Figures 16-18). The error bars indicate one standard deviation from the mean of the maximum area for each time interval. Data points without error bars and with a duration greater than 600 ms consisted of only one maximum area value for that time interval before averaging. Data points without error bars, and with a duration less than or equal to 600 ms, had standard deviations which were smaller than the resolution of the plotter. The curves were calculated by a first order linear regression.



Figures 15A and B: Figure 15A shows the duration of a flash (ms) versus the maximum area attained by that event (km²), for the events of STS-9. Figure 15B is an enlargement of the region in 15A which is bounded by 800 ms and 600 km².



Figures 16A and B: Figure 16A shows the average value of the maximum area (km^2) attained by all events with a given duration, versus the duration of those events (ms), for all flashes. The curve was calculated via a 1st order linear regression. Error bars indicate one standard deviation from the mean maximum area. Figure 16B is the same, except that the outlying point at 1833 ms has been omitted. Points without error bars, and with durations of 600 ms or greater, consisted of only one data point before averaging the area. Points without error bars and with durations less than 600 ms had standard deviations which were smaller than the resolution of the computer plotter.



Figures 17A and B: Same as Figure 16A and B, except that average maximum area values (km^2) are calculated for only the events of STS-51J.

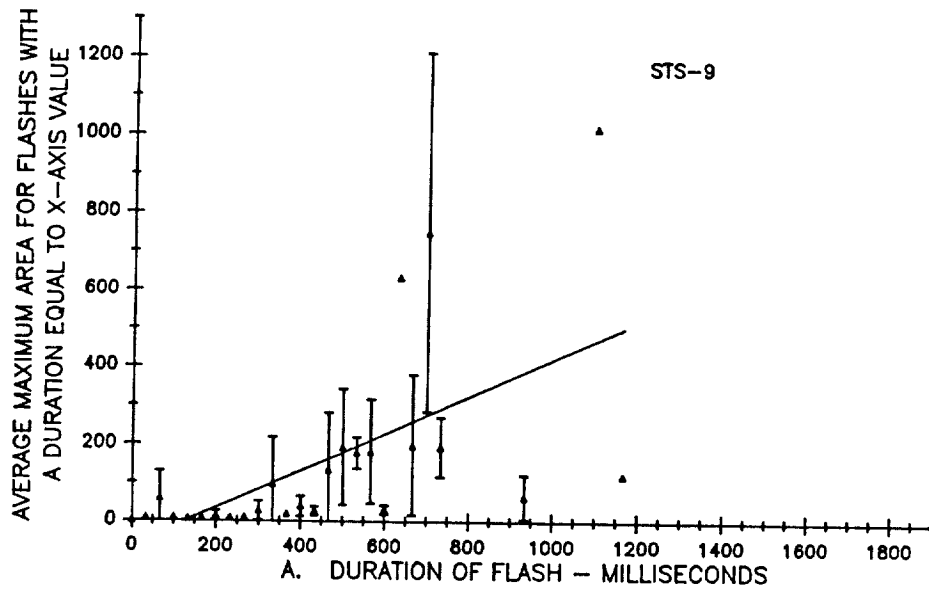


Figure 18: Same as Figure 16A, except that the average maximum area values (km^2) are calculated for only the events of STS-9.

Figure 16B is the same as Figure 16A except that the outlying point at 1833 ms has been excluded. This results in a decrease of the slope of the curve, and a better fit of the curve to the data. This point was also excluded in Figure 17B. Again, the result of doing this was a decrease in the slope of the curve. Figures 16 through 18 more clearly show that in general, larger flashes have longer durations. The correlation coefficients between the average maximum area and duration are 0.67, 0.72, and 0.59 for all flashes, STS-51J flashes, and STS-9 flashes, respectively. The above correlation coefficients are significant at a level of 0.01.

b) Maximum area versus the time that the maximum area occurred.

The time at which the maximum area of an event occurred was investigated. A plot of the number of flashes, which reached their maximum extent at a given time, is shown in Figure 19. This graph indicates an inverse relationship between the time at which the largest area occurred and the number of flashes. More than half of all lightning events reached their maximum area at 200 ms or less. Each of the data points, beyond 633 ms, represent only one event.

The maximum area of each flash was plotted against the time at which that maximum area was attained, for all flashes (Figure 20A). The distribution of the data points appears random, with 90% of the values falling within the region bounded by 5000 km² and 600 ms. The average time to the largest extent of the illuminated region for all flashes was 220 ms, and ranged from 33 ms to 1233 ms. Figure 20B is the same as Figure 20A except that the five data points

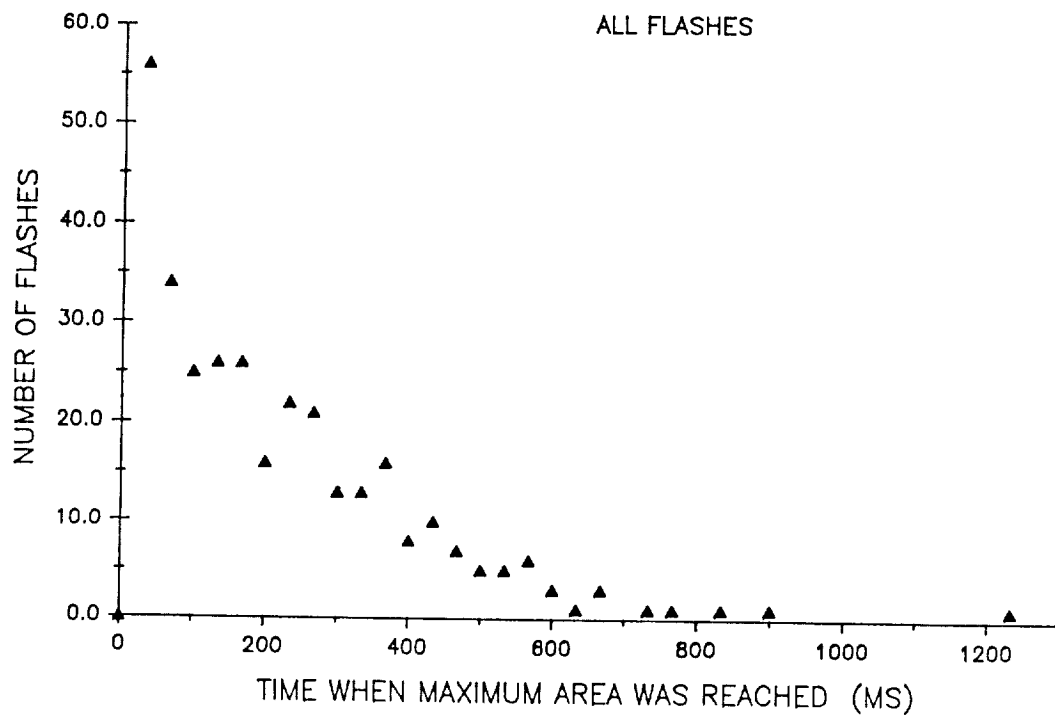
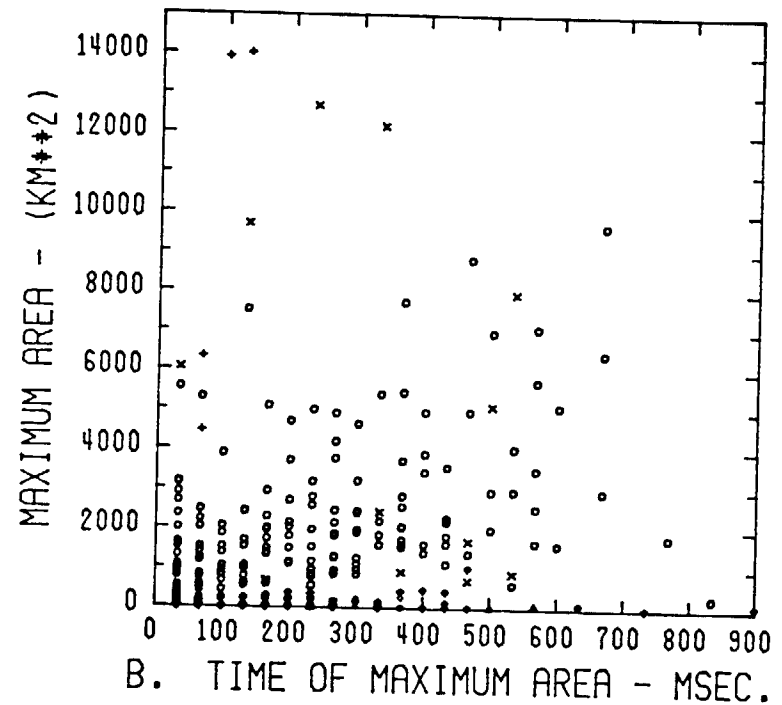
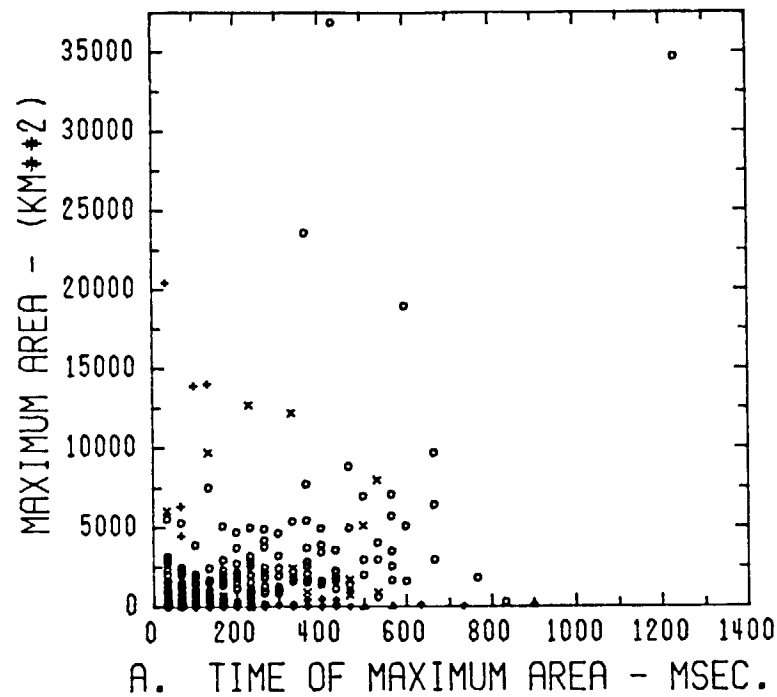


Figure 19: The number of lightning events which attained their maximum area at a given time, versus the time (ms) that the maximum area occurred, for all flashes.



Figures 20A and B: Figure 20A shows the maximum area of a flash (km^2), versus the time that the maximum area occurred (ms), for all events. Figure 20B is an enlargement of the region in 20A which is bounded by 900 ms and 15,000 km^2 . STS-8 (+), STS-9 (x), STS-41D (\diamond), STS-51J (\circ), STS-51Jz (Δ)

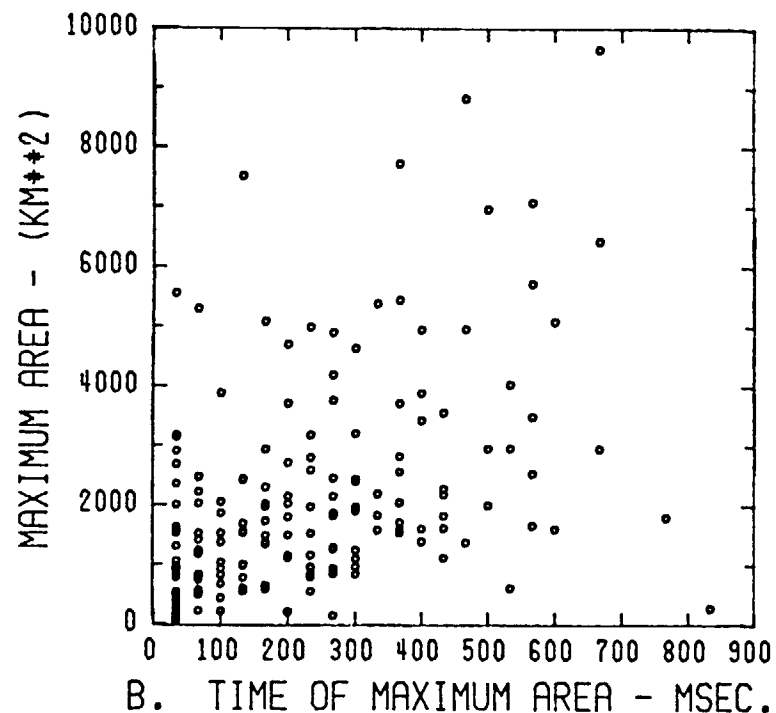
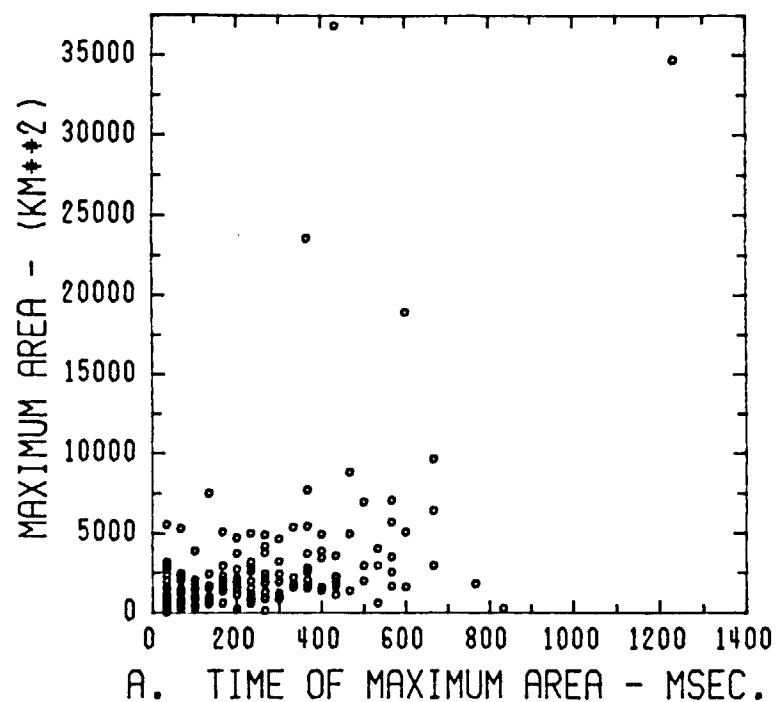
located above 17500 km have been omitted, and the upper time and area limits are 900 ms and 15000 km², respectively.

The maximum area versus the time that the maximum area occurred, was plotted for only those flashes which appeared in the STS-51J video (Figures 21A and B). Figure 21B is an enlargement of the lower left corner of Figure 21A. In Figure 21B there is a slight upward trend in the maximum area as the time at which the maximum area was reached increases. The average time to the maximum area was 234 ms for the STS-51J lightning events. 90% of the data falls within the bounds of 600 ms and 5000 km².

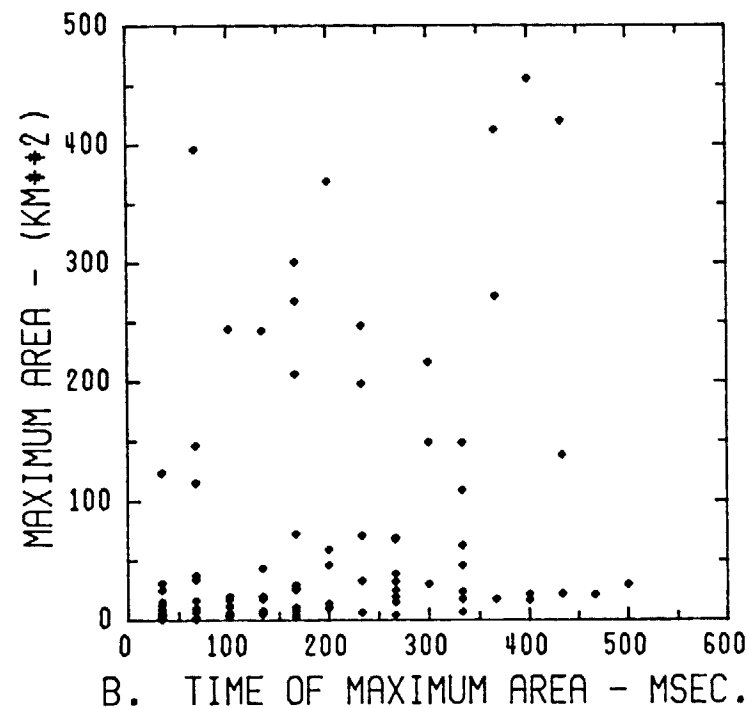
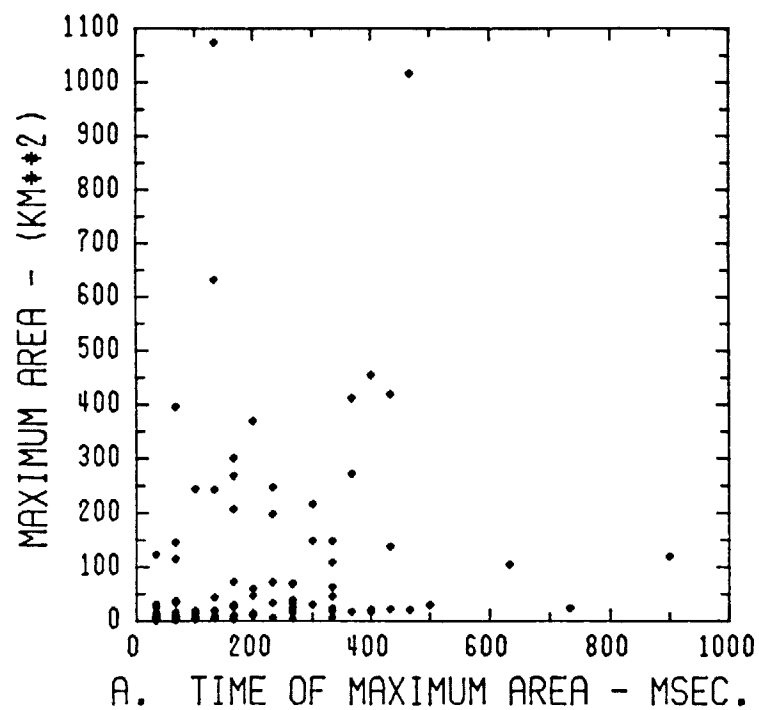
The data from the STS-9 video was plotted in the same manner (Figures 22A and B). In this case, the maximum area and time that the maximum area occurred appear to be two mutually independent variables. 90% of the data from STS-9 falls at or below the region bounded by 500 ms and 300 km². The average time to the maximum area was 194 ms for this group of flashes.

The plots of the variables discussed above are not shown for the flashes of STS-8 and STS-41D because of the small number of data points from each of these videos. The average time to the maximum area was 289 ms for the STS-8 flashes and 71 ms for the STS-41D flashes.

The maximum area was averaged for each time at which the maximum area occurred. The average maximum area was then plotted against each corresponding value of time (Figures 23-25). In this series of figures the error bars indicate one standard deviation from the value of the average maximum area. Points without error bars



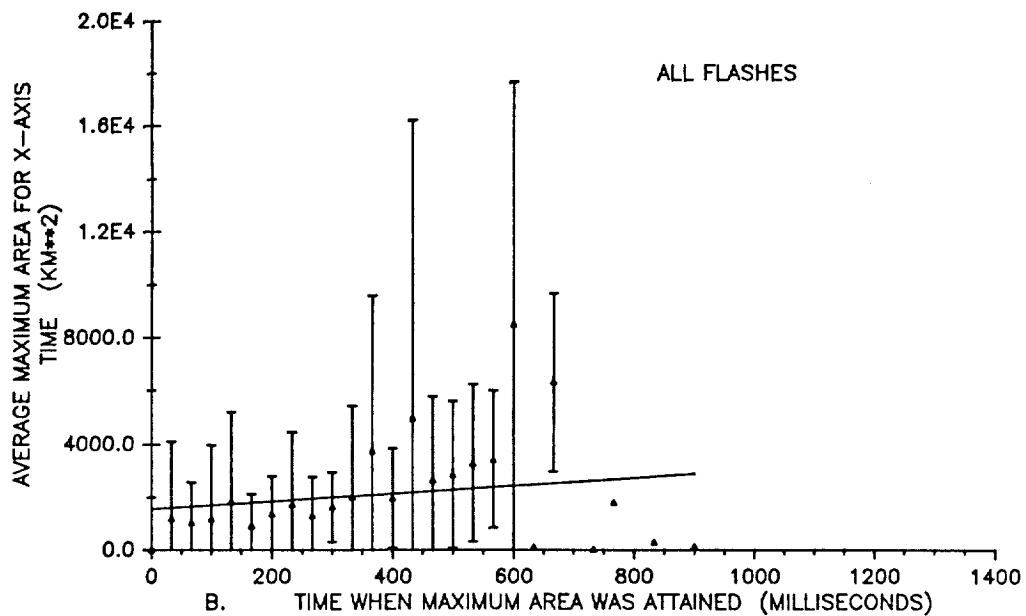
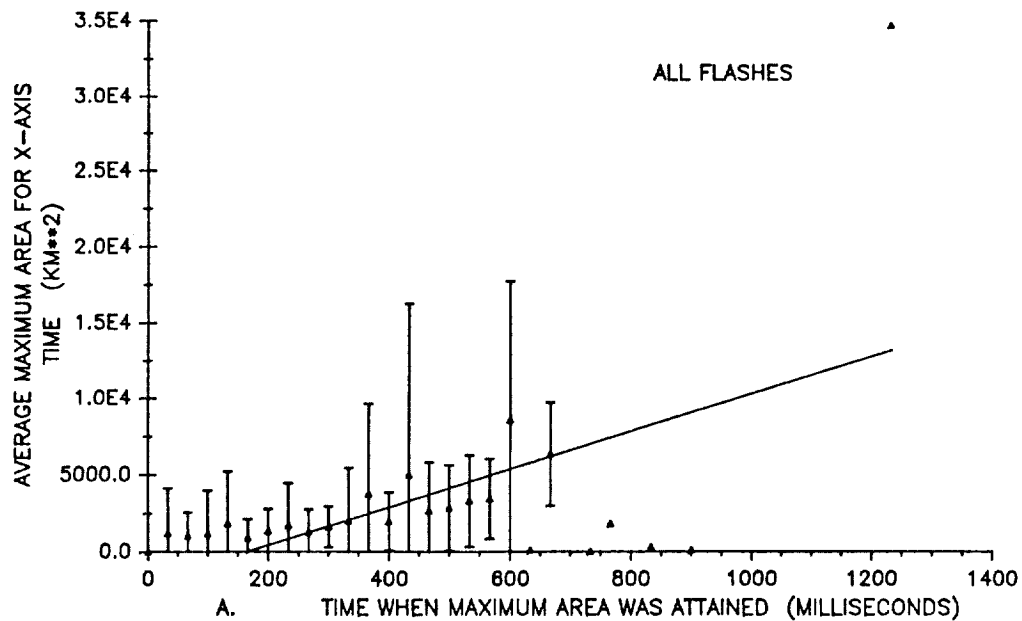
Figures 21A and B: Figure 21A shows the maximum area of a flash (km^2), versus the time that the maximum area occurred (ms), for the events of STS-51J. Figure 21B is an enlargement of the region in 21A which is bounded by 900 ms and 10000 km^2 .



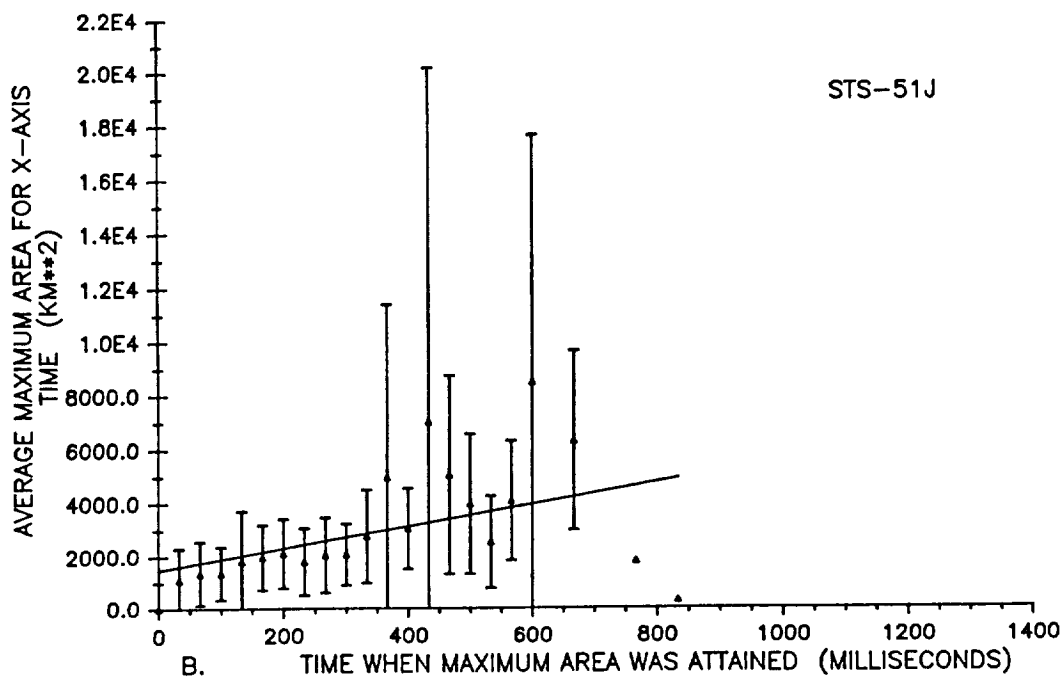
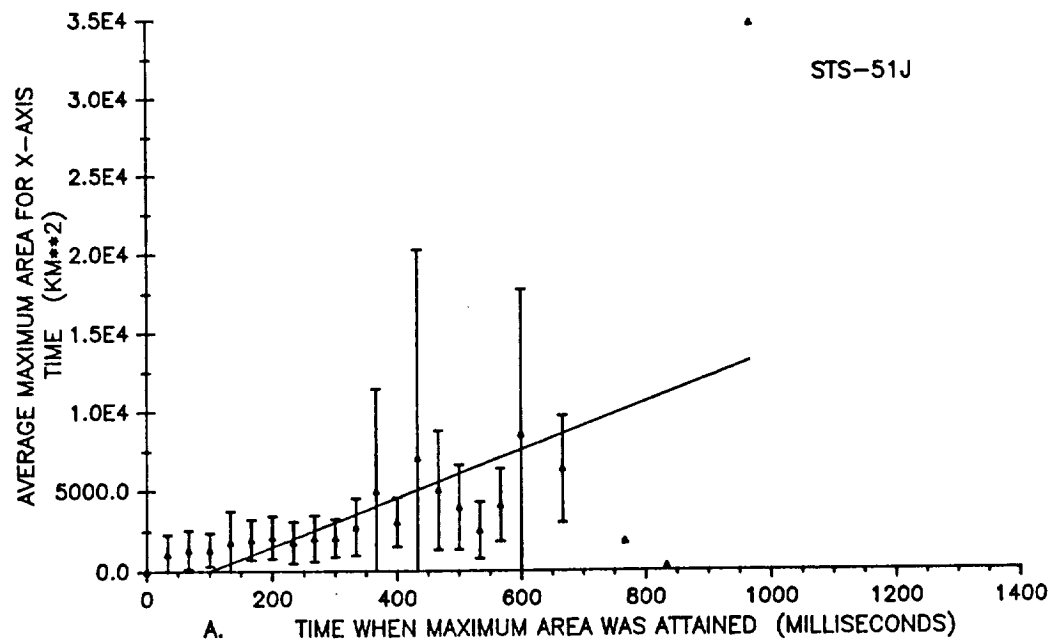
Figures 22A and B: Figure 22A shows the maximum area of a flash (km^2), versus the time that the maximum area occurred (ms), for the events of STS-9. Figure 22B is an enlargement of the region in 22A which is bounded by 600 ms and 500 km^2 .

consisted of only one value for that time before averaging. The curve was calculated by a first order linear regression. The trend of increasing average maximum area with increasing time to the maximum area, in Figures 23A and 24A, implies that larger flashes take longer to reach their maximum dimensions than smaller flashes. This increasing trend is very slight for the flashes of STS-9 (Figure 25). The correlation coefficients, between the average maximum area and the time to that maximum area, are 0.55, 0.69, for all flashes and for STS-51J flashes, respectively, at a 0.01 level of significance. The correlation coefficient between the average maximum area and the time to that maximum area for the events of STS-9 is 0.17 at a 0.30 level of significance.

If the lone data point at 1233 ms is ignored, it significantly changes the curves which appear in Figures 23A and 24A. The curves, calculated without this point, are shown in Figures 23B and 24B. The curve for all flashes now more closely resembles that of the STS-9 flashes, while the curve for the STS-51J flashes still indicates an upward trend in average maximum area as the time to that maximum area increases. It must be kept in mind that the average area values for the STS-9 events were up to 100 times smaller than those of the other videos. Thus the slope of the curve for all flashes (Figure 23A) is likely to be influenced by these small values, especially beyond 600 ms. Though not shown, the curve of average maximum area versus time when the maximum area occurred for STS-41D follows a trend which is similar to that shown for all flashes. The correlation coefficient between the average maximum



Figures 23A and B: Figure 23A shows the time (ms) at which the maximum area of a flash occurred, versus the average value of the maximum area (km^2) of all events reaching their maximum area at a given time, for all 323 flashes. The error bars indicate one standard deviation from the mean area. The curve was calculated via a first order linear regression. Points without error bars consisted of one value of maximum area before averaging. Figure 23B is the same as 23A except that the point at 1266 ms has been omitted.



Figures 24A and B: Figure 24A is the same as Figure 23A, except that the mean maximum area values are calculated only for the events of STS-51J. Figure 24B is the same as 24A, except that the outlying point at 966 ms has been omitted.

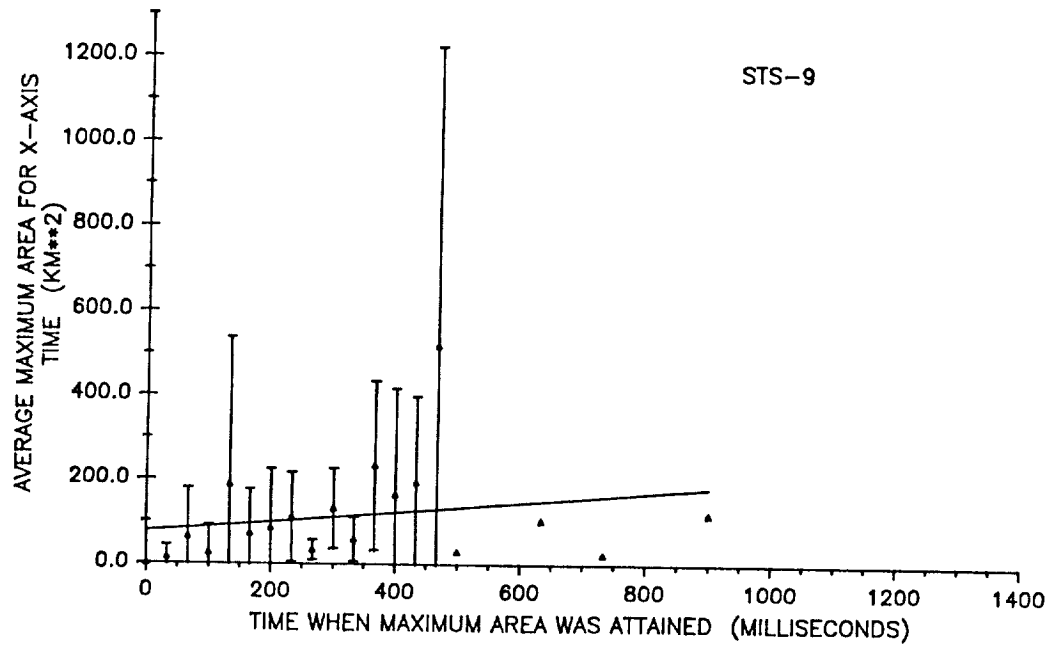


Figure 25: Figure 25 is the same as Figure 23A, except that the mean maximum area values are calculated only for the events of STS-9.

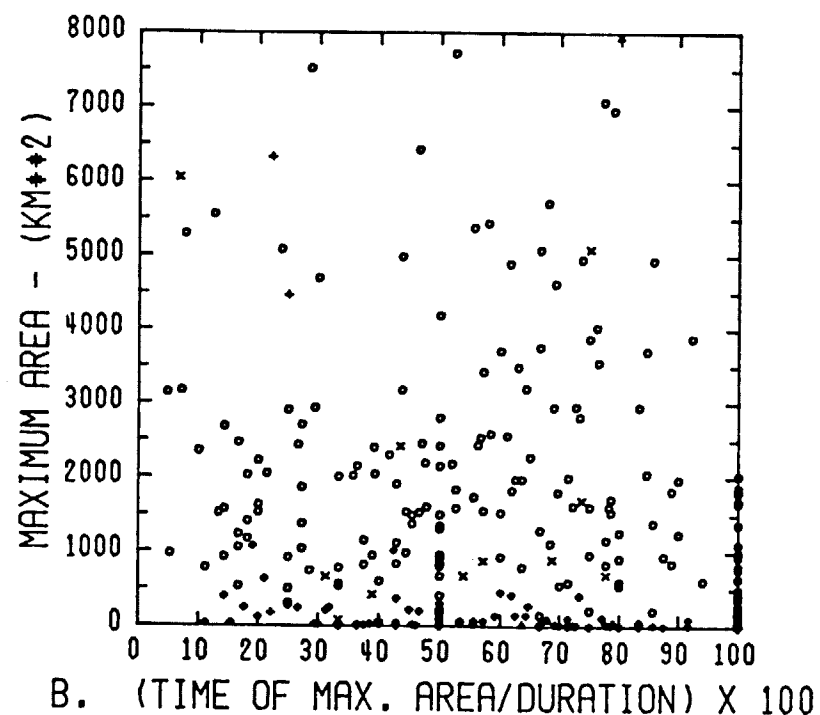
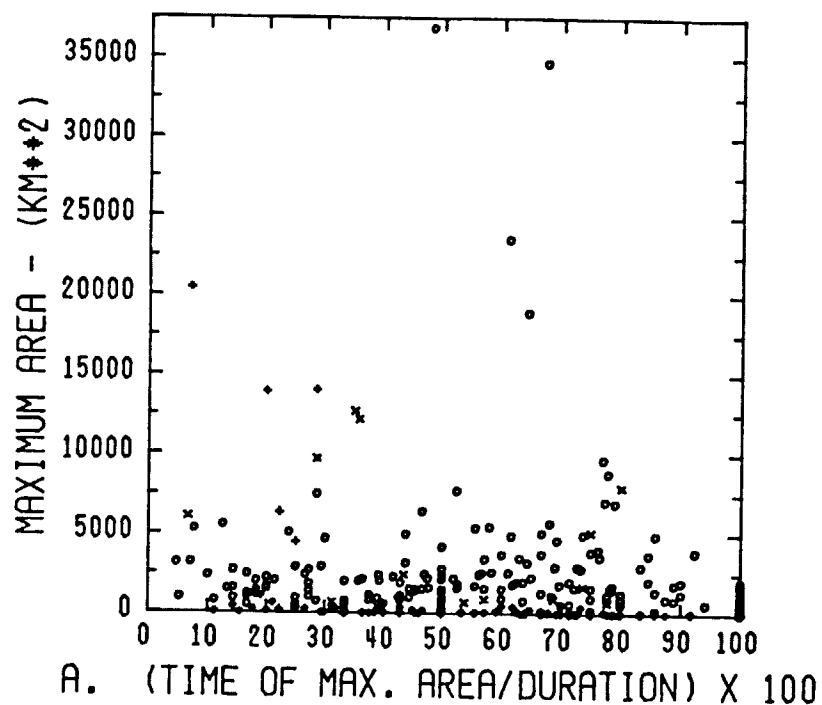
area and the time that that maximum area occurred was 0.55 at a 0.20 level of significance for the STS-41D data set. The same type of curve for the events of STS-8 indicated a slight decreasing trend. The correlation coefficient for the STS-8 data set was -0.23 at a 0.30 level of significance.

c) Maximum area versus the percent of the lifetime of the flash at which the maximum area occurred.

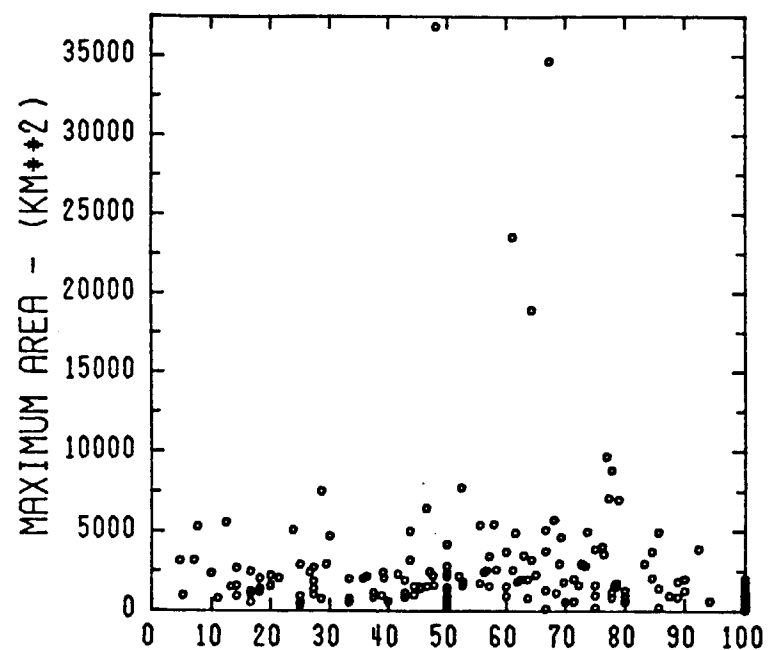
The time at which the maximum area occurred was divided by the total duration of the flash, and then plotted against the maximum area of the flash to determine if larger flashes reach their peak area at a greater percent of their total duration than smaller flashes. The percent of the total lifetime of a flash that passed by when the largest area was reached, for all flashes, is shown in Figure 26A. Figure 26B is the same plot except that the upper bound of the maximum area is 8000 km^2 . The values of the percent of the total duration when the maximum area occurred ranged from 0.5% to 100%.

A time ratio equal to 100% indicates that the maximum area occurred on the final video frame in which the flash appeared. 70% of the 45 events which attained their maximum extent at 100% of their duration, existed for only 100 ms or less. On average, the maximum area occurred at 58% of the total duration of the flash.

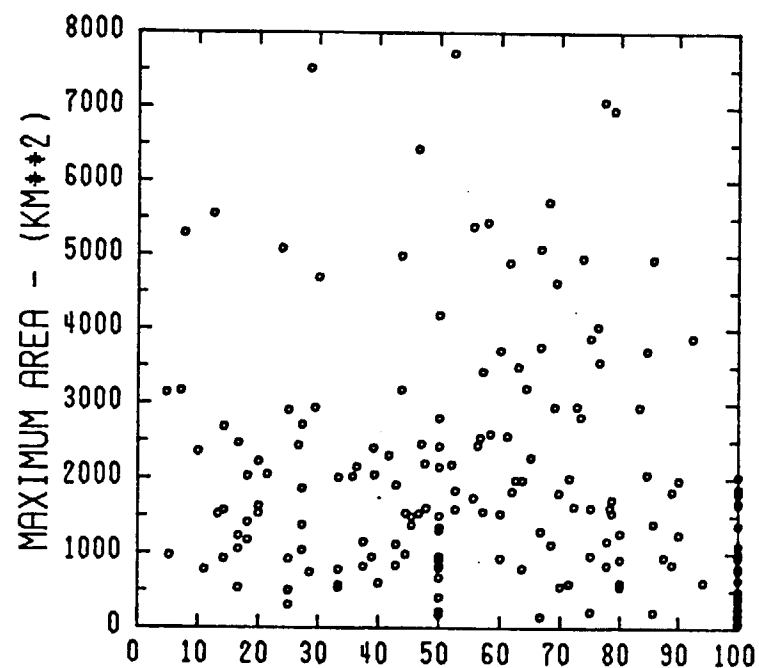
The data points in Figures 26A and B appear randomly distributed. This is also true for similar plots of the data from the STS-51J flashes (Figures 27A and B), and the data from the STS-9 events (Figures 28A and B). The average value of the percent of



Figures 26A and B: Figure 26A shows the maximum area of a flash (km^2), versus the percent of the total duration of that flash at which the maximum area occurred. Figure 26B is an enlargement of the region in 26A bounded by 8000 km^2 and 100%. STS-8 (x), STS-9 (\diamond), STS-41D (+), STS-51J and 51Jz (o).

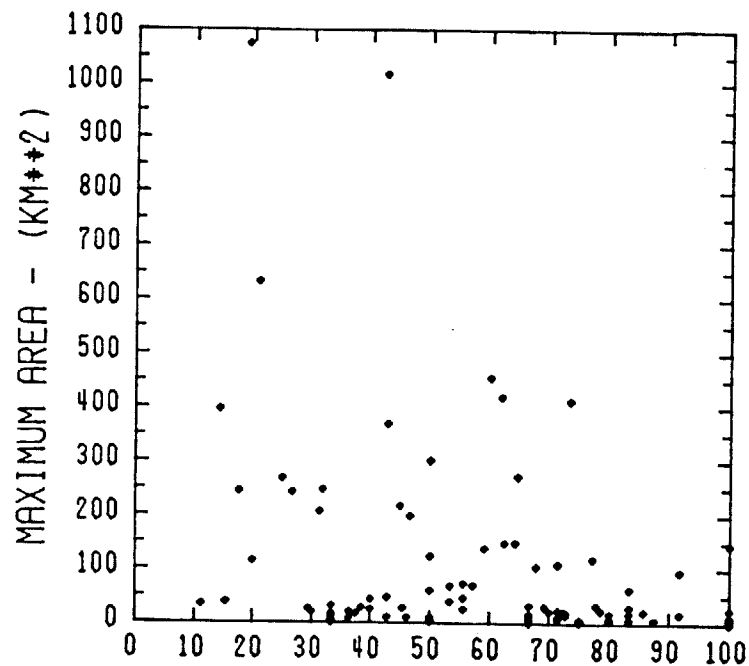


A. (TIME OF MAX. AREA/DURATION) X 100

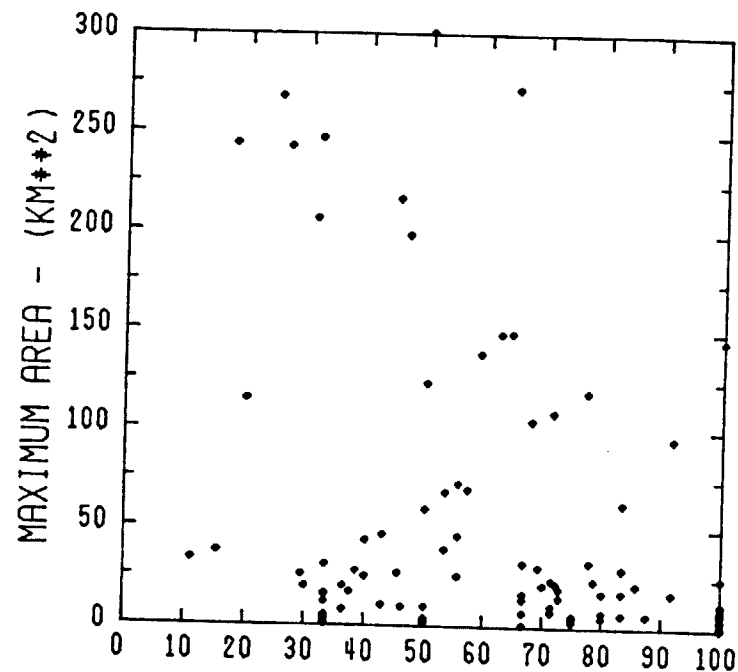


B. (TIME OF MAX. AREA/DURATION) X 100

Figures 27A and B: Figure 27A is the same as Figure 26A, except that only those points from the STS-51J lightning events are shown. Figure 27B is an enlargement of the region in 27A which is bounded by 8000 km^2 and 100%.



A. (TIME OF MAX. AREA/DURATION) X 100



B. (TIME OF MAX. AREA/DURATION) X 100

Figures 28A and B: Figure 28A is the same as Figure 26A, except that only those points from the STS-9 lightning events are shown. Figure 28B is an enlargement of the region in 28A which is bounded by 300 km² and 100%.

the total duration of a flash at which the maximum area occurred was 59% and 61% for the STS-51J and STS-9 flashes, respectively. The plots from the STS-8 and STS-41D flights are not shown because of the small number of data points. The average value of the ratio of the time to the maximum area divided by the total duration was 33% for STS-41D and 48% for STS-8.

The number of flashes that reached their maximum area within a given percent of their total duration is shown in Figure 29. The number of flashes was summed over each 10% interval. On average, as the percent of the total duration of a flash at which the maximum area occurred increases, the number of flashes also increases. This indicates that the lightning events had a tendency to attain their maximum dimensions toward the later half of their lifetime. The greatest number of flashes, 51, fell in the 90-100% interval. There were also 49 flashes in the 70-80% interval. Only a few flashes reached their maximum area within 0-10% of their total duration.

The values of the maximum area of the illumination, shown in Figures 26-28 were averaged for each 10% interval of the time ratio. The average maximum area was then plotted versus each 10% time ratio interval (Figures 30A-C). The error bars indicate one standard deviation from the average value of the maximum area. Even after averaging the maximum area, a constant increasing or decreasing trend between these two variables is not apparent for the STS-51J flashes (Figure 30B). The average area decreases until the time ratio equals 40%, and then increases with a maximum at the 60% to 70% time ratio. However, a slight decreasing trend of average

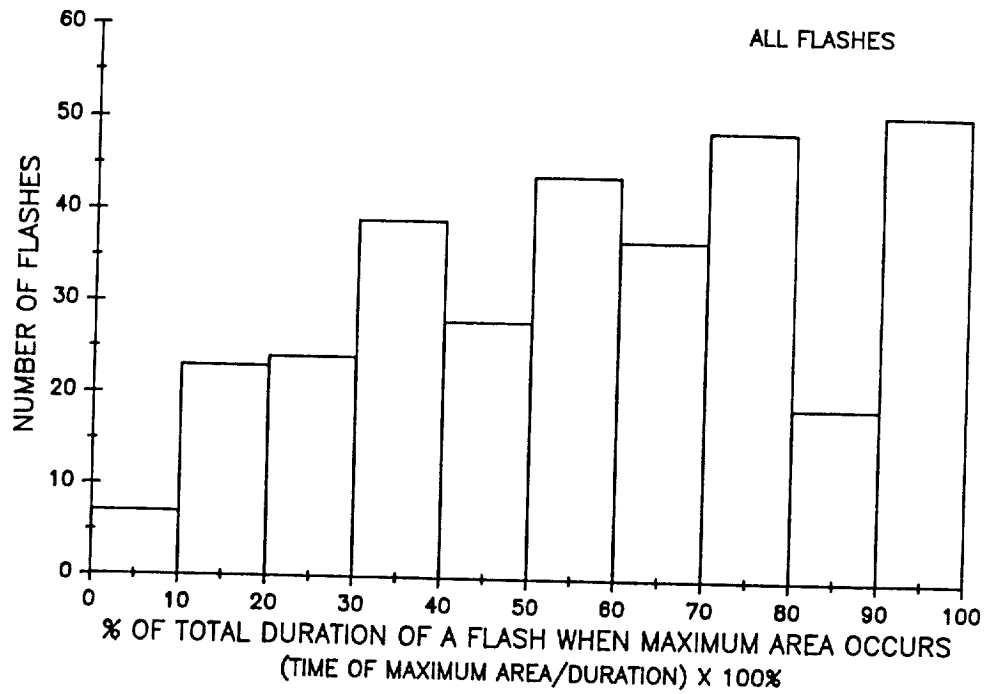
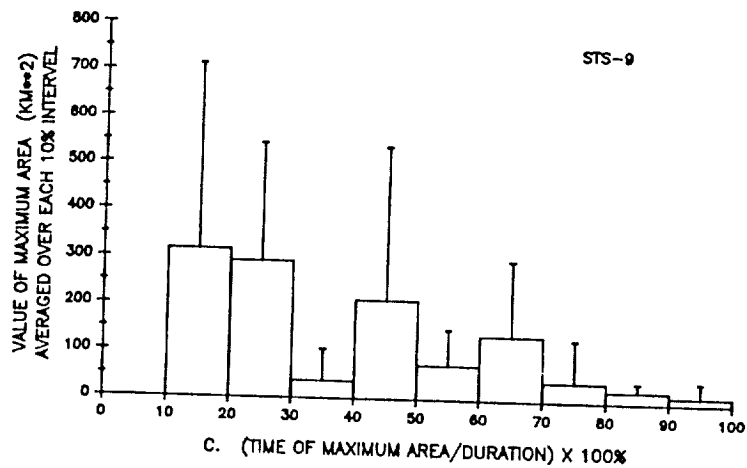
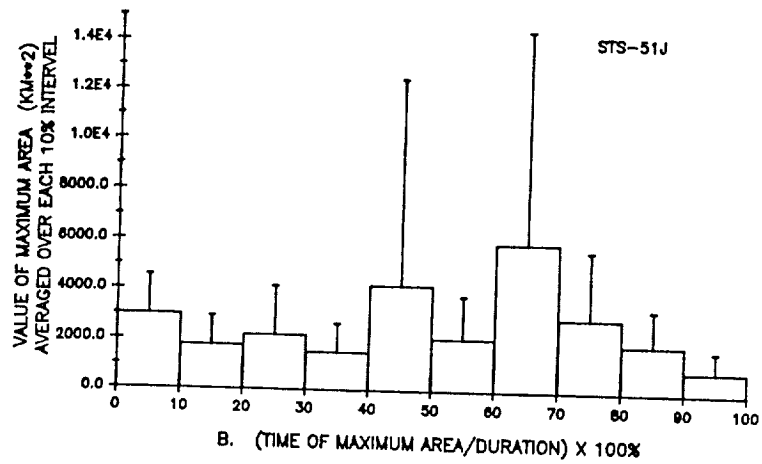
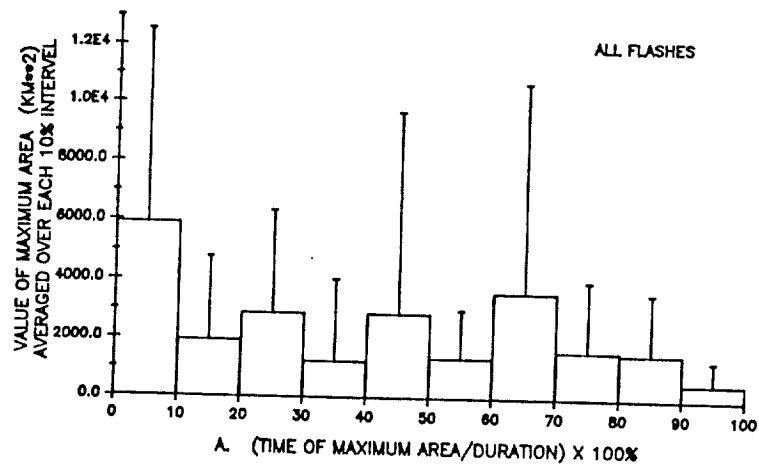


Figure 29: Figure 29 indicates the number of flashes whose maximum area occurred at a given percent of their total duration. The number of flashes has been summed over each 10% interval.

Figures 30A, B, and C: Figures 30A - C show the mean value of the maximum area (km^2) of the events, which attained their maximum area within a given percent of their total duration, for all events, the events of STS-51J, and the events of STS-9, respectively. To attain the mean areas, the areas plotted in Figures 26 - 28 were averaged for each 10% interval.



maximum area exists for all flashes together (Figure 30A). This decreasing trend is much stronger for those events of STS-9 (Figure 30C). This implies that larger flashes reach their maximum extent earlier in their lifetime than smaller flashes. The correlation coefficient between these two variables are -0.61, -0.03, and -0.80 for all flashes, STS-51J flashes, and STS-9 flashes, respectively. The correlation between the average maximum area and the time ratio interval is significant at a level of 0.05 for all flashes and 0.01 for the events of STS-9, respectively. The data from STS-51J is not best represented by a linear regression, as the correlation is not significant even at the 0.50 level. Although not shown, the events of STS-41D exhibited the same type of decreasing trend in the average maximum area that occurred for the STS-9 events. The trend of decreasing average maximum area with increasing time ratio did not span the entire range of the data, for the events of STS-8. However, a strong decreasing trend did exist from the time ratio value of 20% to 70% for the STS-8 flashes. The correlation coefficients between the average maximum area and the percent of the total duration at which that maximum area occurred for STS-41D and STS-8 are -0.80 and -0.37, at the 0.10 and 0.20 level of significance, respectively.

4. Changes in the Area of a Flash Over its Lifetime.

a) Peaks in the area curve.

Changes in the size of the region illuminated by a lightning event were examined by plotting the area of a flash over its lifetime

(Figures 50 through 81.) On average, there were 3.6 peaks in the area curve per flash. The number of peaks per flash ranged from one to fourteen. The lightning of STS-41D had the smallest average number of peaks per flash, and the narrowest range of only one to four peaks per flash. The average number and range of peaks per flash for each flight, and for all flashes are shown in Table V.

b) The time interval between the peaks in the area curve.

The average time between the peaks in the area curve of a flash was found for all flashes and for each flight (Table V). The average interpeak time interval was longest for the flashes of STS-8, and STS-9, and shortest for the flashes of STS-41D. The average values of the interpeak intervals for each flight are within 20 ms of each other. 65% of the interpeak intervals, for all flashes, had a duration of 100 ms or less (Figure 31). Less than 10% of all the interpeak intervals had durations which exceeded 200 ms. There is no data point at 33 ms in Figure 31 because at least three video frames must be viewed in order to see a peak, minimum, and peak in the area of the illumination. The total elapsed time for this peak to minimum to peak area series must be at least 66 ms long. The percent of interpeak intervals of a given duration for flights STS-51J, STS-9, STS-8, and STS-41D are shown in Figures 32A and B, and 33A and B, respectively. 86% of the interpeak intervals of STS-51J lasted 133 ms or less. Approximately 76% of the interpeak intervals of STS-9, STS-8, and STS-41D had durations less than or equal to 133 ms. The general trend of the data for each flight indicates that as the interpeak interval increases the

Table V: Peaks in the Area Curve - A summary of the number of peaks per flash, and the time interval between two peaks, to the first peak, and between a minimum and the subsequent peak in the area curve.

FLIGHT	ALL*	STS-51J	STS-41D	STS-8	STS-9
AVERAGE NUMBER OF PEAKS/FLASH	3.6	4.2	2.4	4.0	2.7
RANGE OF NUMBER OF PEAKS/FLASH	1-14	1-14	1-4	2-8	1-9
AVERAGE TIME INTERVAL BETWEEN PEAKS (ms)	110	106	100	120	120
AVERAGE TIME TO INITIAL PEAK (ms)	67	54	62	87	86
AVERAGE TIME FROM A MINIMUM TO THE FOLLOWING PEAK IN THE AREA CURVE (ms)	51	50	33	53	56

* All refers to average values for all 323 lightning events.

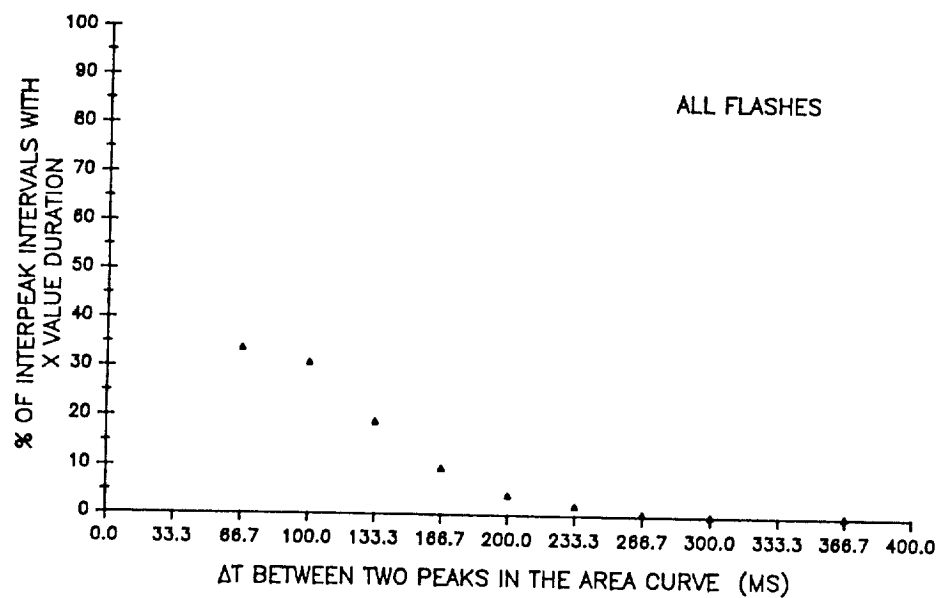


Figure 31: The length of the time interval between two peaks in the area curve of an event (ms), versus the percent of all interpeak time intervals with a given duration, for all 323 flashes.

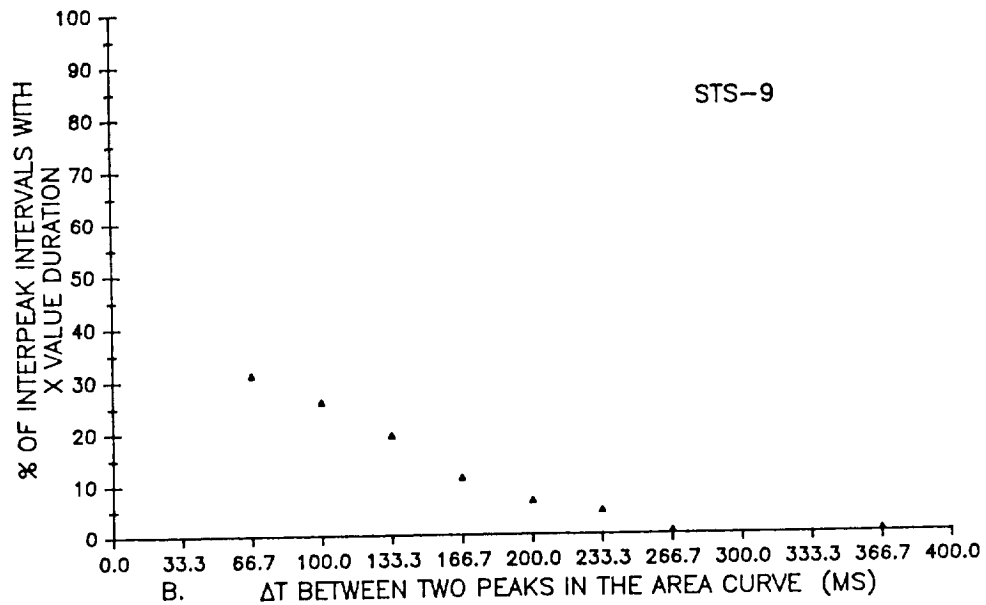
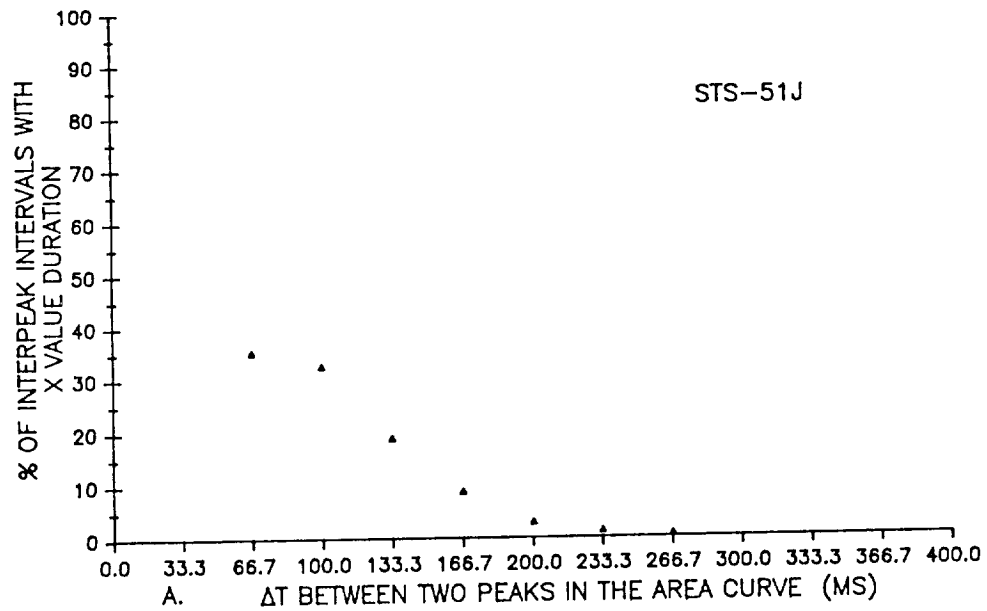


Figure 32A and B: The length of the time interval between two peaks in the area curve of an event (ms), versus the percent of all interpeak time intervals with a given duration, for the events of STS-51J (Figure 32A) and those of STS-9 (Figure 32B).

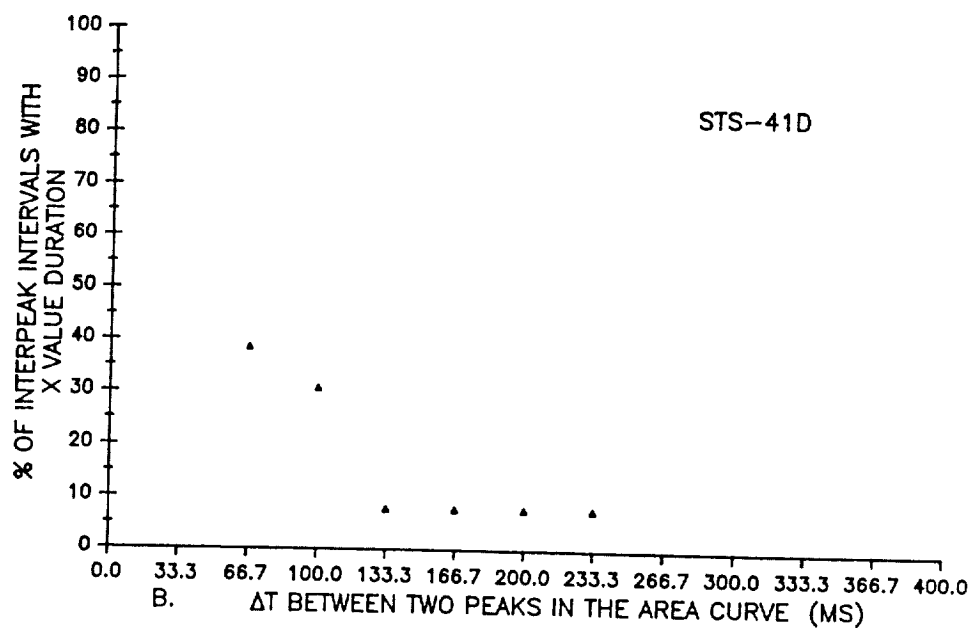
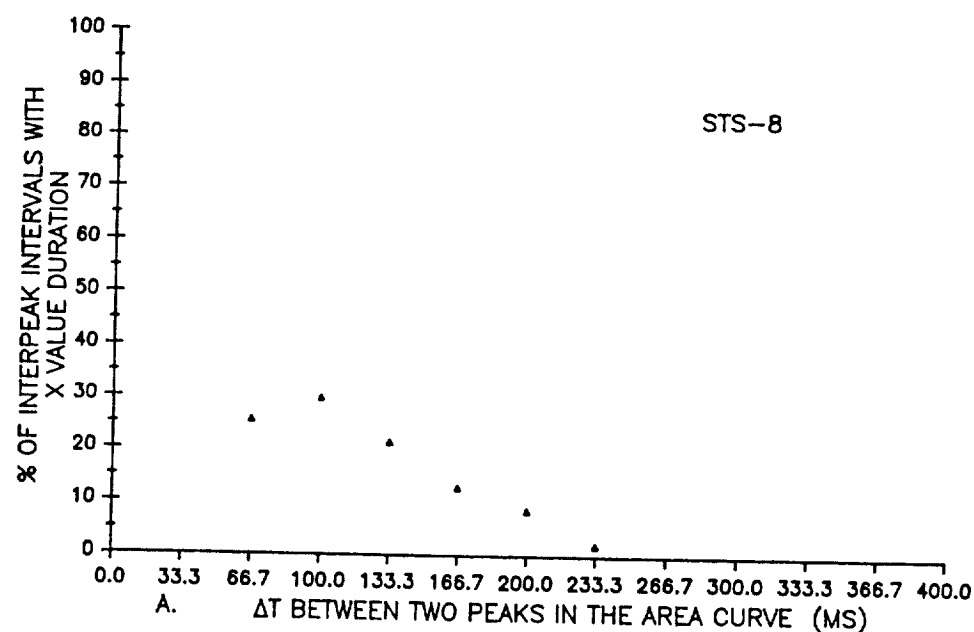


Figure 33A and B: The length of the time interval between two peaks in the area curve of an event (ms), versus the percent of all interpeak time intervals with a given duration, for the events of STS-8 (Figure 33A) and those of STS-41D (Figure 33B).

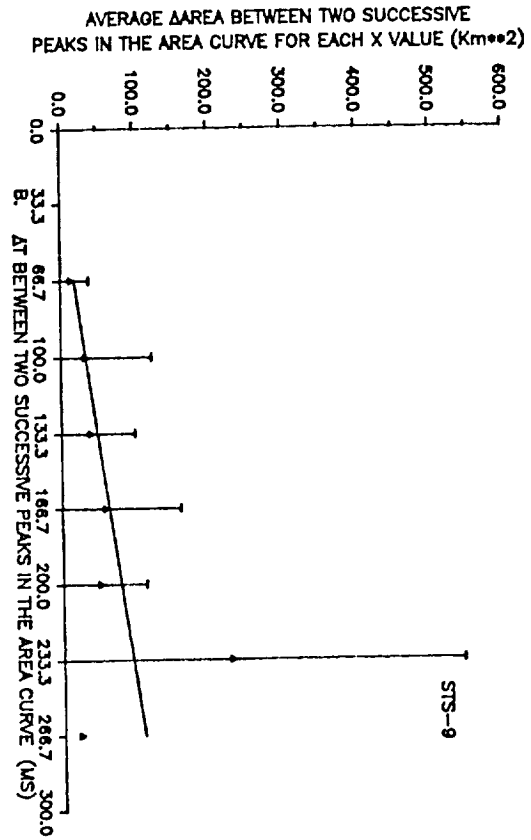
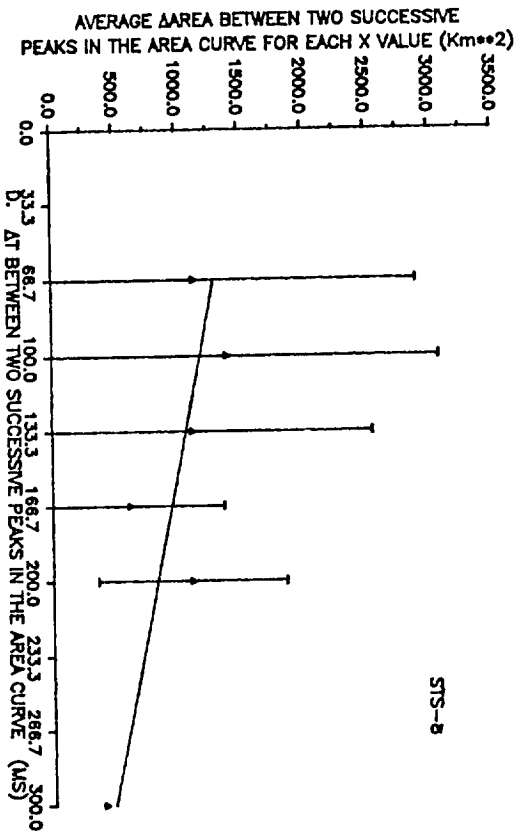
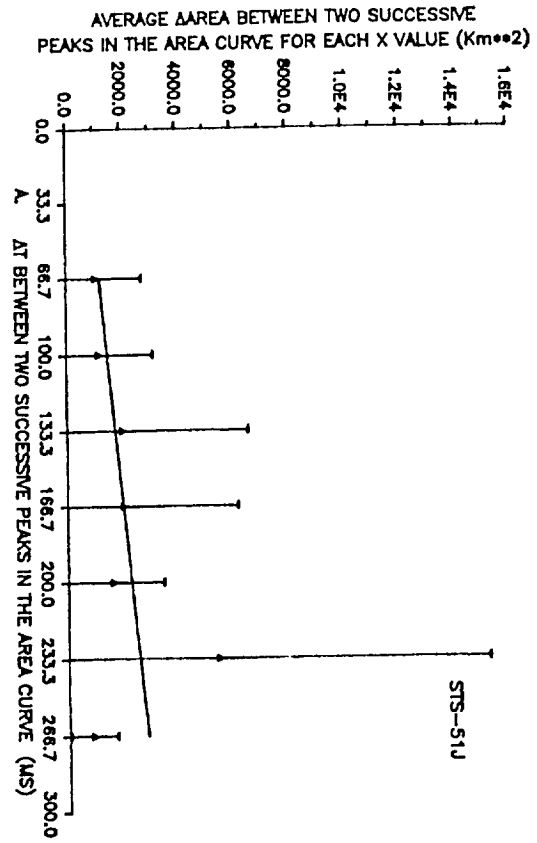
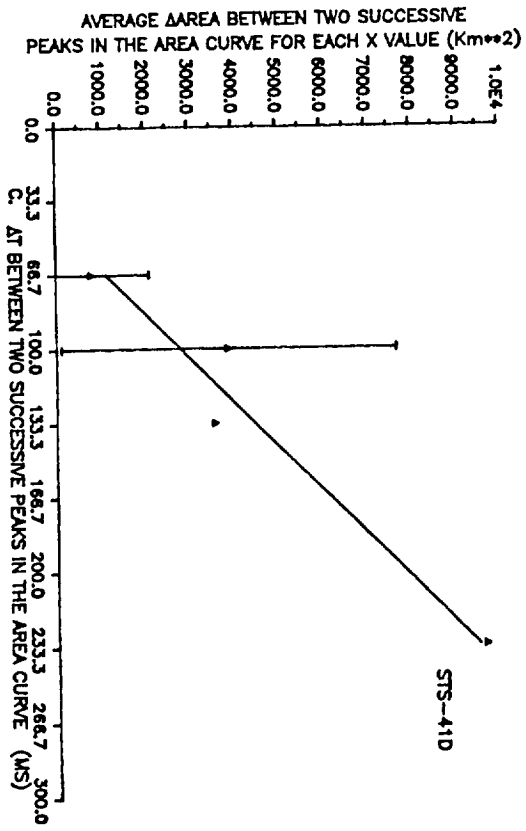
percent of values at each time decreases, with only a very small number of interpeak intervals exceeding 166 ms.

c) Changes in the area between peaks.

The average absolute change in the area from one peak to the next was approximately 1130 km^2 , for all flashes. The absolute change in the area between two successive peaks was compared to the interpeak time interval over which that change occurred. The values of this change in area were averaged for each interpeak time interval of a given duration. This was done, in order to determine if longer interpeak time intervals corresponded to greater changes in the area between peaks. The value of the average change in area between peaks, for all flashes, was found to increase as the length of the interpeak time interval slowly increased.

The above procedure was repeated for the flashes of each flight. The average absolute change in the area from one peak to the next for STS-51J, STS-9, STS-8, and STS-41D was 1460 km^2 , 40 km^2 , 1120 km^2 , and 3000 km^2 , respectively. For the flashes of STS-51J, STS-9, and STS-41D, it was found that as the absolute change in the area between two peaks, averaged for each interpeak time interval, increased, the length of the interpeak time interval also increased (Figure 34A-C). This increasing trend was greatest for the flashes of STS-41D. The flashes of STS-8 did not exhibit this increasing trend (Figure 34D). In fact, the absolute change in the area between peaks, averaged for each interpeak time interval, was found to decrease as the interpeak time interval increased. The correlation coefficient between the absolute change in the area

Figures 34A-D: Figures 34A-D show the time interval between two peaks in the area curve versus the average of the absolute change in area that occurred during that time period for flights STS-51J, STS-9, STS-41D, and STS-8, respectively. The error bars indicate one standard deviation from the average area. Points without error bars consisted of only one value before averaging. The curve was calculated by a first order linear regression. With the exception of the STS-8 events, as the time interval increases, the average of the absolute change in area between two successive peaks also increases.



between two peaks, averaged over a given time interval, and the interpeak time interval was 0.38, 0.44, and 0.97 for STS-51J, STS-9, and STS-41D, respectively, while that for STS-8 was -0.78. The correlations are significant at a level of 0.25, 0.20, 0.025, and 0.05 for STS-51J, STS-9, STS-41D, and STS-8, respectively.

d) **The time to the first peak in the area curve versus the time to subsequent peaks.**

On average, the time to the initial peak in the area curve, for all flashes, was 67 ms. 87% of the time intervals to the initial peak lasted 100 ms or less (Figure 35). The time to the first peak in area ranged from 33 ms to 266 ms.

The average time between subsequent minimums in the area curve to the following peak was 51 ms for all flashes. Approximately 97% of the values of the minimum to peak time interval had durations of 100 ms or less (Figure 35). Almost 15% more of these time intervals had a duration of 33 ms, when compared to the time to the initial peak in area values. Only 1% of the minimum to the following peak time intervals, and 6% of the time to the initial peak in area time intervals lasted 166 ms or more.

The shift of the subsequent minimum to peak time intervals towards smaller values is also visible, in varying degrees, when the percent of values falling within a given subsequent minimum to peak time interval are plotted for each flight individually. 98% of the subsequent minimum to peak time intervals for STS-51J had durations of 100 ms or less, while 94% of the time to the initial peak in area values fell into this same duration interval (Figure 36A). 93% of

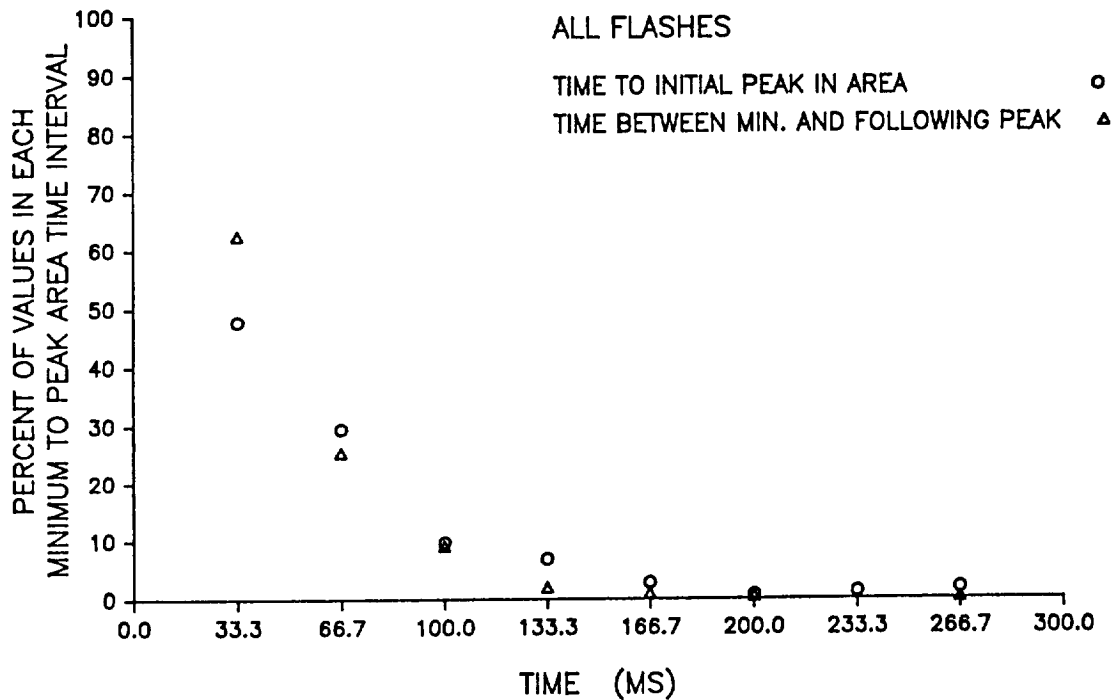


Figure 35: The time interval (ms) to the initial peak in the area curve (o), and the time interval (ms) between all other minimums to the following peak in the area curve (Δ) versus the percent of values with a given minimum to peak area time interval, for all 323 lightning events. At 100 ms and 200 ms, the two data sets overlap. Notice the shift to a greater percent of smaller values for the time interval between the subsequent minimum to peak in the area curve.

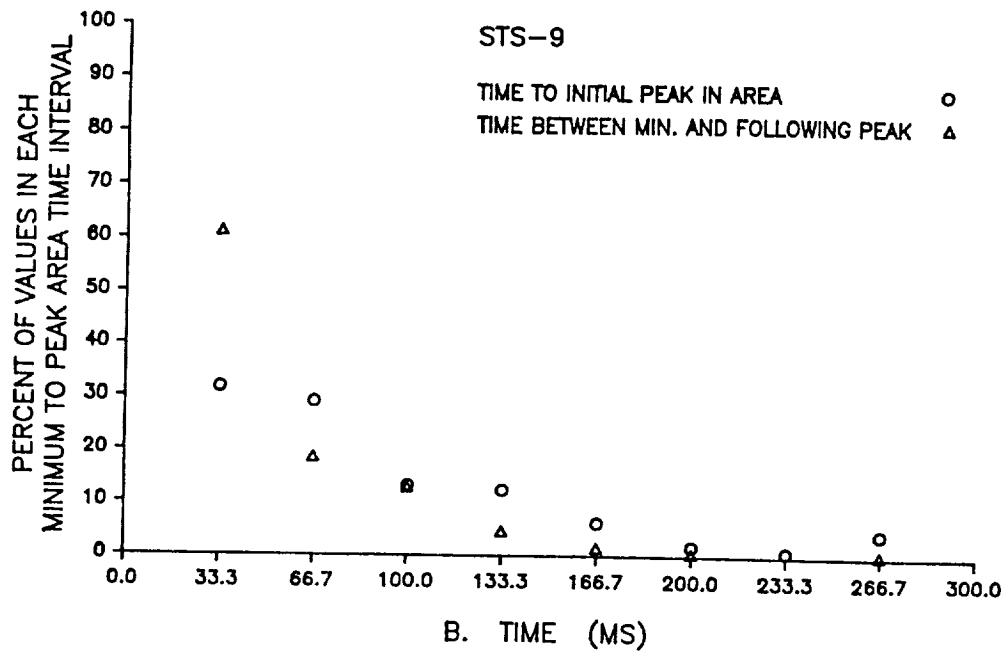
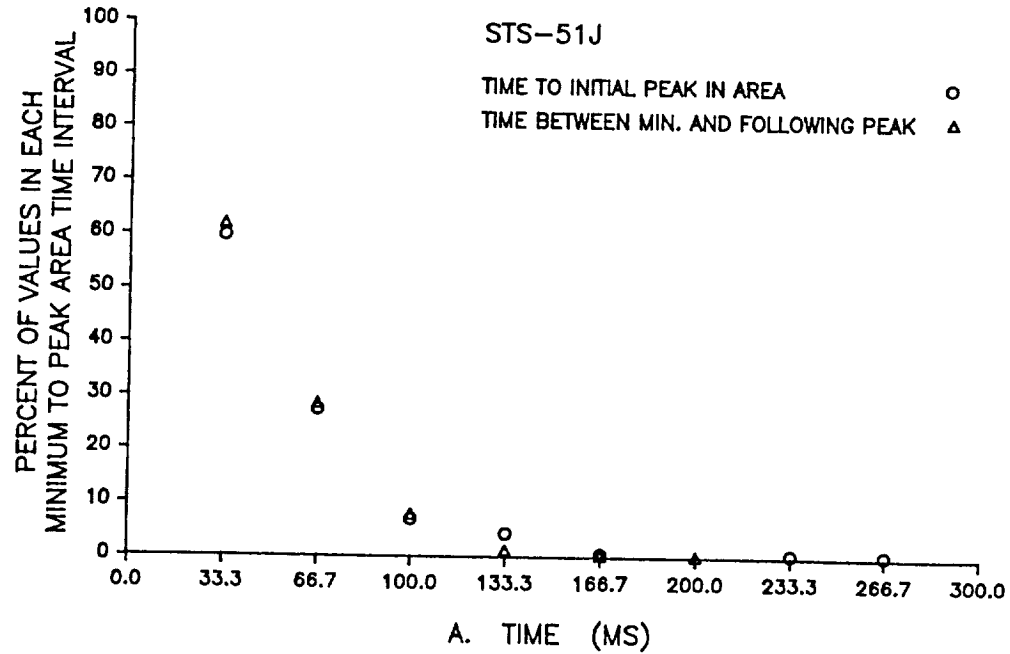


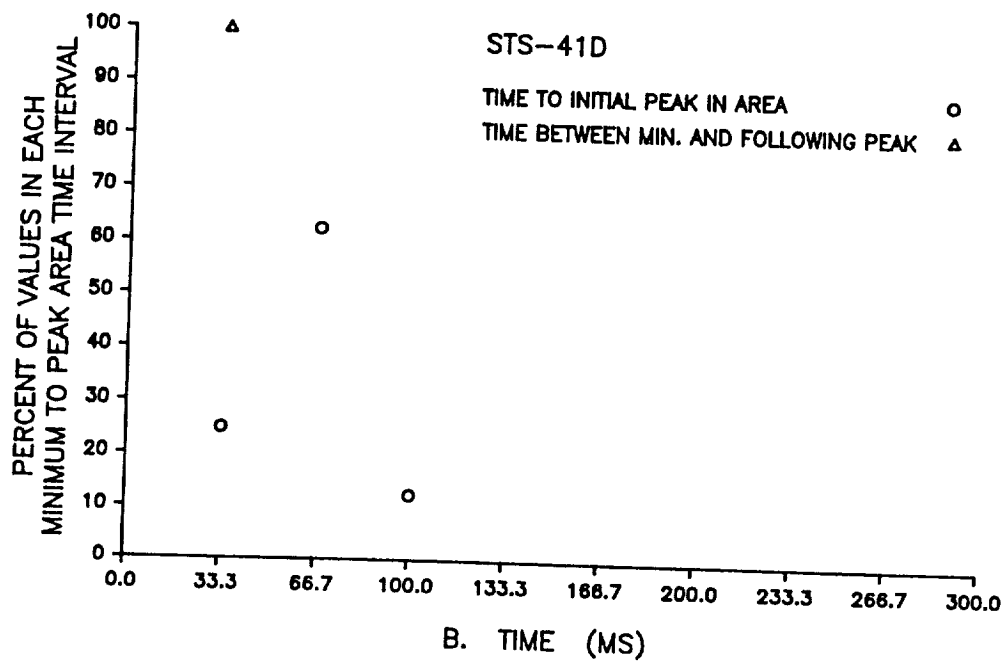
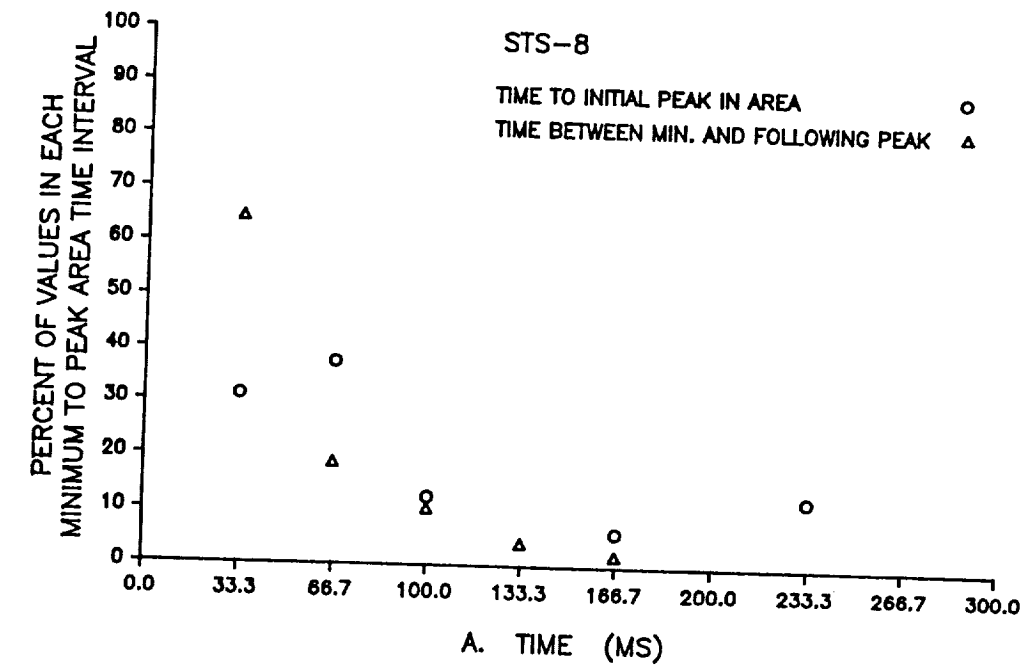
Figure 36A and B: Same as Figure 35, but for the events of STS-51J (Figure 36A) and those of STS-9 (Figure 36B). Note that the data sets overlap at 166 ms in Figure 36A, and at 100 ms in Figure 36B.

the subsequent minimum to peak time intervals for STS-9 had durations of 100 ms or less, while 74% of the time to the initial peak in area values had this same duration (Figure 36B). For the lightning events of STS-8, 94% of the values of the time between a subsequent minimum to the following peak in area, and 81% of the values of the time to the initial peak in the area had durations of 100 ms or less (Figure 37A). For STS-41D, all the values of the subsequent minimum to peak time interval had a duration of 33 ms, while only 25% of the time to the first peak intervals had this duration. All of the values of the time to the initial peak in the area, for STS-41D, were less than or equal to 100 ms (Figure 37B).

In each of the four data sets, the average time to the first peak in the area curve was larger than the average time from a subsequent minimum to the following peak in the area curve (Table V). The largest difference between these two average values was found for the flashes of STS-41D, where the average time to the initial peak in the area was 47% larger than the average time between subsequent minimums and peaks in the area.

e) The change in the area versus the time interval from a minimum to peak in the area curve.

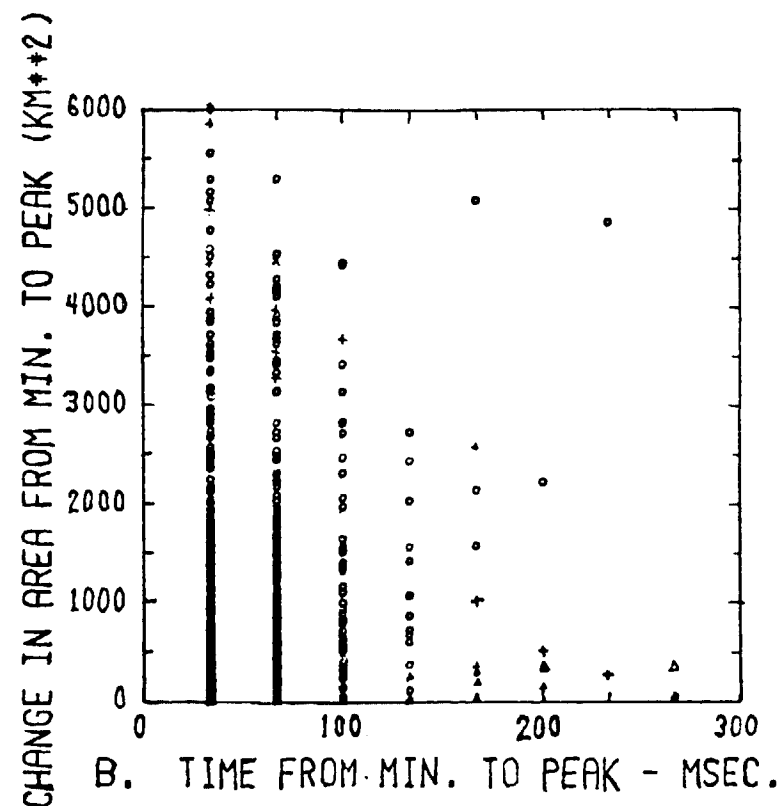
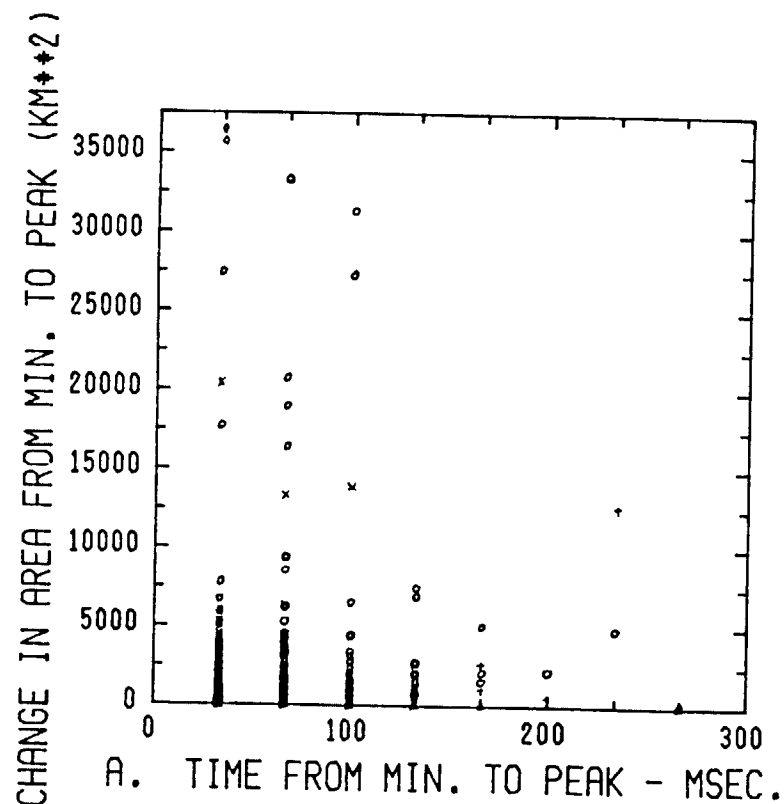
The change in the area from a minimum to the following peak in the area curve was plotted against the time it took for that change in area to occur. The change in area versus time, for both the initial and subsequent peaks, were included in these plots. The change in the area, from a minimum to the peak in the area curve, versus the time over which that change occurred, for all flashes, is



Figures 37A and B: Same as Figure 35, but for the events of STS-8 (Figure 37A), and STS-41D (Figure 37B).

shown in Figure 38A. Figure 38B is the same as 38A except that the upper area bound has been decreased to 6000 km^2 , resulting in a loss of 25 data points. For all events, an average change in area of 1100 km^2 occurred over an average time interval of 56 ms. At first glance, Figures 38A and B appear to indicate an inverse relationship between these two variables. However, 95% of the 1100 data points plotted in each of these two figures lie below 4000 km^2 . Also as time increases, the number of data points decreases dramatically.

The change in area, from a minimum to the following peak in the area curve, was averaged at each time and then plotted for each time (Figure 39). After averaging the area at each time, the relationship between these two variables looks quite different from that shown in Figures 38A and B. The curve, which was calculated by a first order linear regression, indicates a weak positive correlation between these two values, for all flashes. The error bars in Figure 39 indicate one standard deviation from the mean area at any given time. The data point at 266 ms is not very representative of an average value over all flashes because six of the seven data points averaged together at 266 ms are from the STS-9 lightning events. If we choose to ignore this point, the slope of the curve increases, thus indicating a stronger correlation between these two values. Only the first three points in Figure 39 involved values of the change in area from all four flights. Data from three of the four flights were averaged together to get the points from 133 ms to 233 ms.



Figures 38A and B: Figure 38A shows the time interval from a minimum to a peak in the area curve (ms), versus the change in the area (km^2) over that time interval, for all 323 events. Figure 38B is an enlargement of the region in 37A which is bounded by 300 ms and 6000 km^2 . STS-8 (+), STS-9 (Δ), STS-41D (x), STS-51J and 51Jz (o)

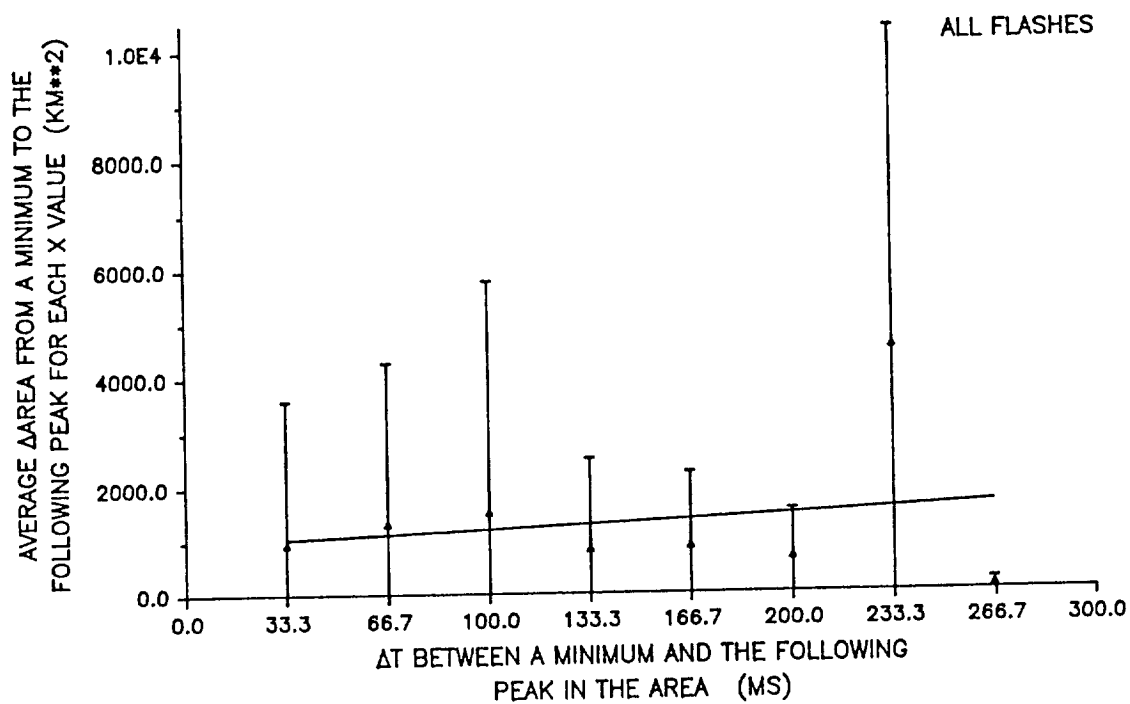
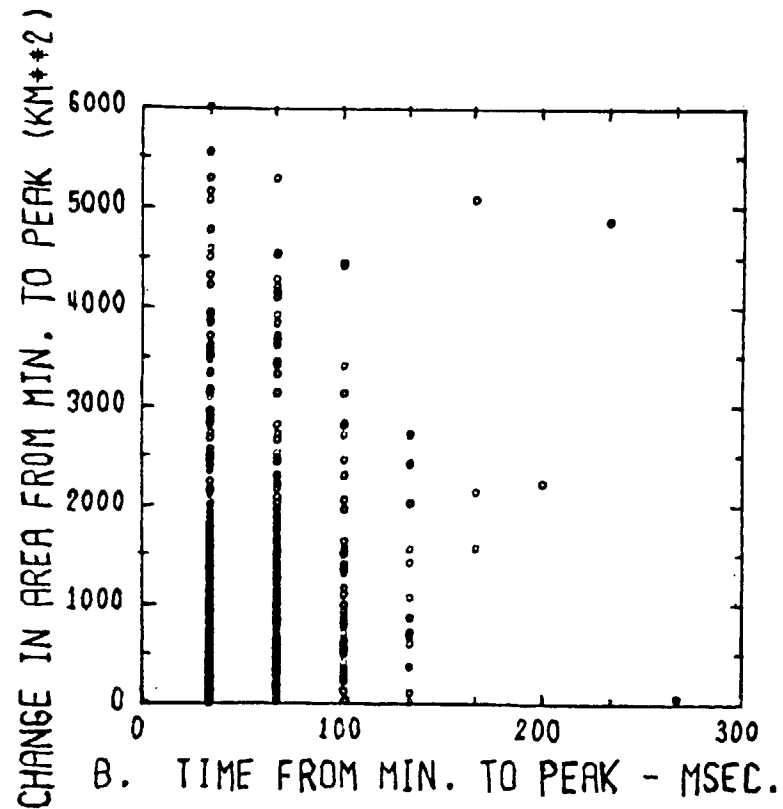
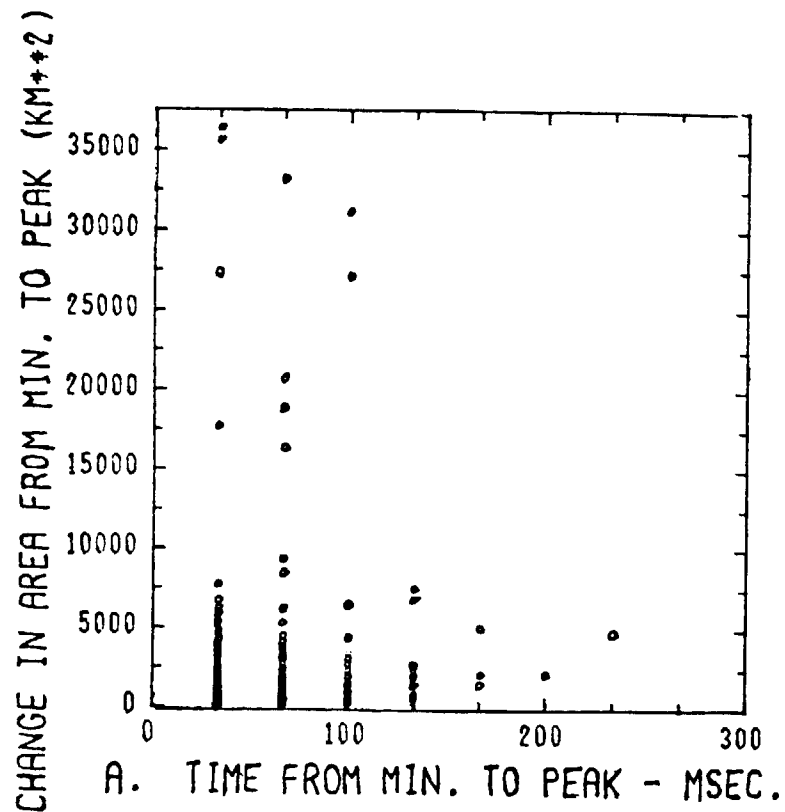


Figure 39: The average of the change in area (km^2) (shown in Figures 38A and B) during a given minimum to peak time interval, versus that time interval (ms), for all 323 events.

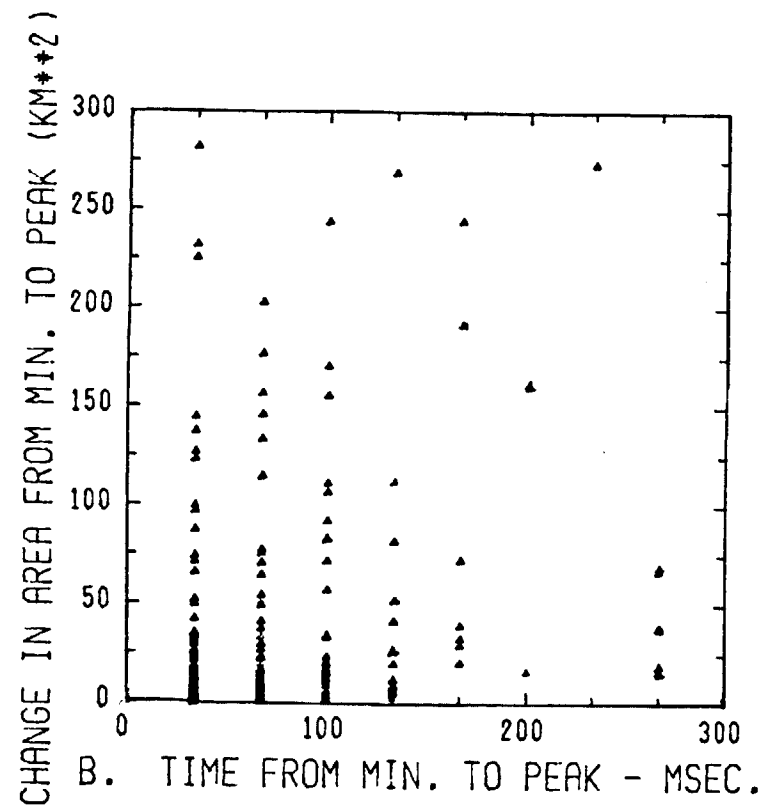
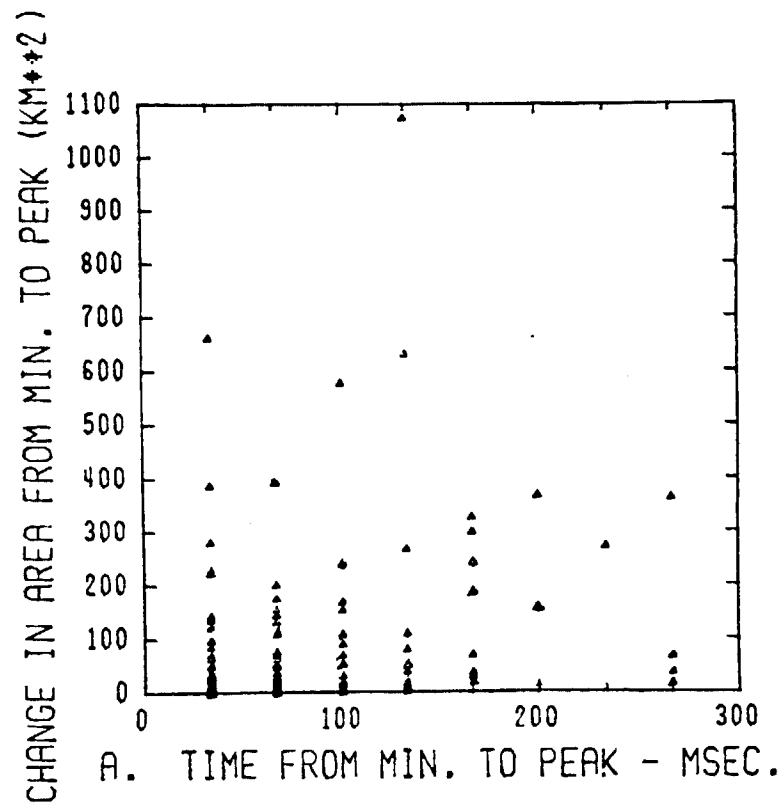
When the change in area versus the time from a minimum to the following peak in the area curve was plotted for the lightning events of STS-51J, 95% of the data fell into the region bounded by 4000 km² and 133 ms (Figures 40A and B). For the events of STS-51J, an average minimum to peak change in the area of 1440 km² occurred over an average time period of 50 ms.

The change in the area versus the change in the time, from a minimum to a peak in the area curve, was plotted for the flashes of STS-9 (Figures 41A and B). The average minimum to peak change in the area, 45 km², occurred over an average time interval of 68 ms. The value of the average change in area for the STS-9 events is two orders of magnitude smaller than the average change in area for all flashes, as well as for STS-51J, STS-8, and STS-41D flashes. In comparison to the other data sets, the STS-9 events had the smallest average change in the area over the largest average time interval, from a minimum to the following peak in the area curve. The lightning events of STS-9 had the smallest range of the change in the area values. 90% of the data fell within the region bounded by 150 km² and 200 ms.

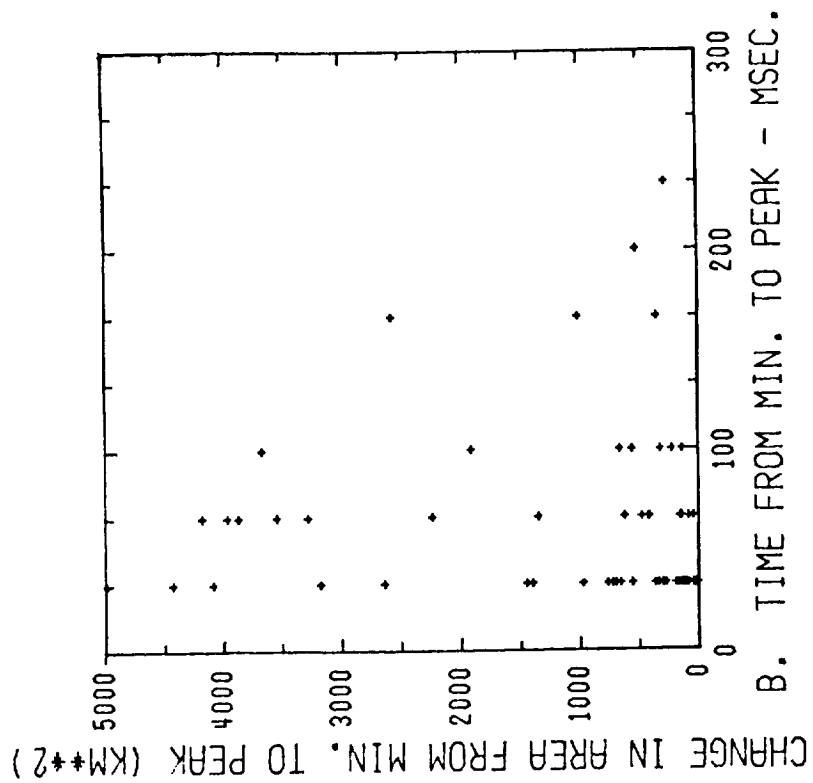
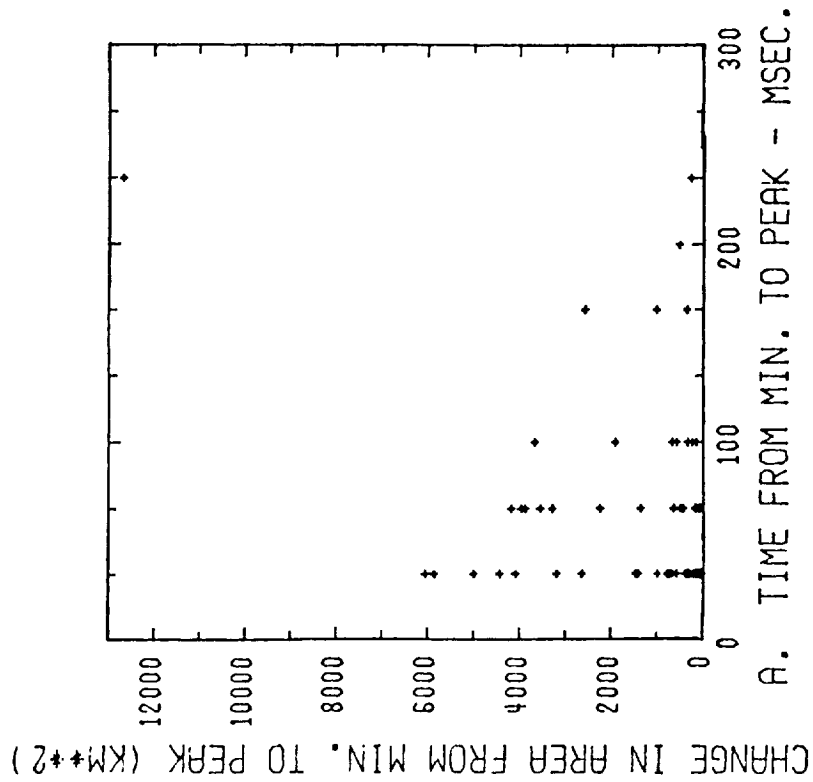
The same type of figure was plotted for the flashes of STS-8 (Figures 42A and B). 90% of the data points fell in the region bounded by 5000 km² and 100 ms. For the lightning of STS-8, an average change in area from the minimum to the following peak in the area curve of 1395 km² occurred over an average time interval of 63 ms.



Figures 40A and B: Figure 40A is the same as Figure 38A, except that only the STS-51J data points are shown. Figure 40B is an enlargement of the region in 40A which is bounded by 300 ms and 6000 km².



Figures 41A and B: Figure 41A is the same as Figure 38A, except that only the STS-9 data points are shown. Figure 41B is an enlargement of the region in 41A which is bounded by 300 ms and 300 km^2 .



Figures 42A and B: Figure 42A is the same as Figure 38A, except that only the STS-8 data points are shown. Figure 42B is an enlargement of the region in 42A bounded by 300 ms and 5000 km².

Almost all of the minimum to peak area time intervals of STS-41D lasted 66 ms or less (Figures 43A and B). During an average minimum to peak area time interval of 43 ms, an average change in area of 3310 km^2 occurred. Of all four groups of flashes, the events of STS-41D had the shortest average time interval between a minimum to peak in the area curve, and the largest average change in the area during this time interval.

For each set of flashes, the plots of the change in the area from a minimum to a peak in the area curve, versus the time interval over which this change occurred show the same trend that appeared in the plot for all flashes. That is, as the change in the area increases, the time interval over which this change occurs appears to decrease. Figures 41 through 43 also show that most of the time intervals from a minimum to the following peak in the area curve had a duration of 100 ms or less.

The change in the area from a minimum to the following peak was averaged at each time. Then, the average change in area was plotted against the corresponding time interval for each set of flashes (Figures 44A and B, and 45A and B). In all four of these figures, the curve was calculated by a first order linear regression. The error bars indicate one standard deviation from the average change in the area at each time. Points without error bars consisted of only one value for that time interval before averaging.

The curve for STS-51J shows a slight increasing trend in the average change in the area with time. This curve indicates a weak correlation between the average change in area and the time

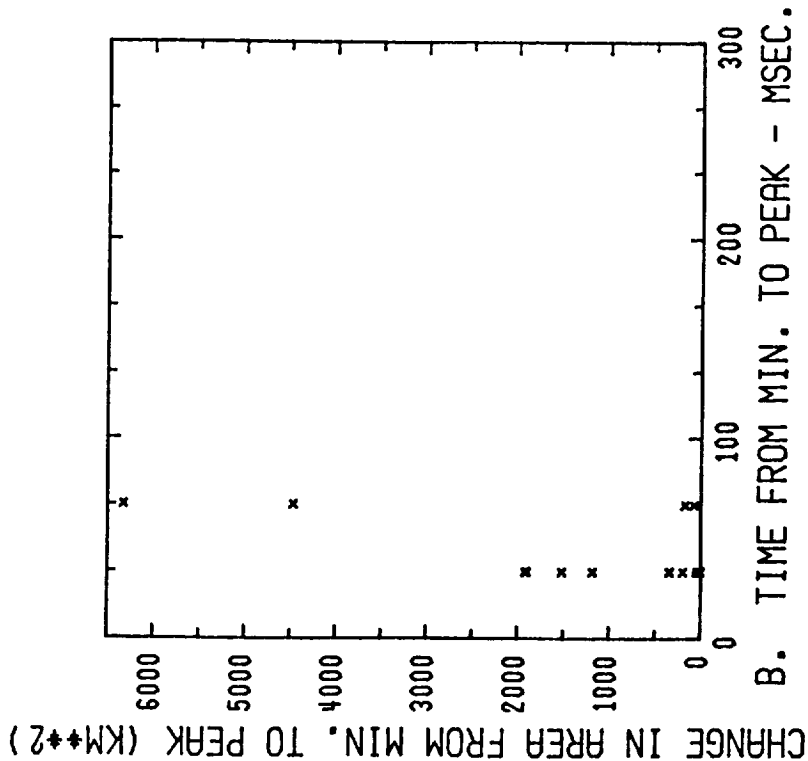
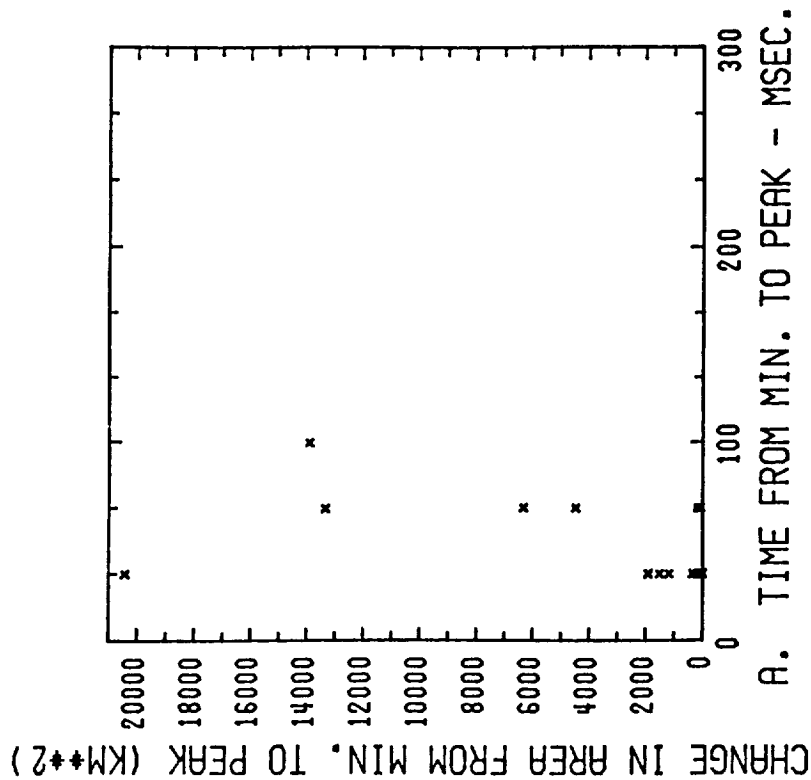
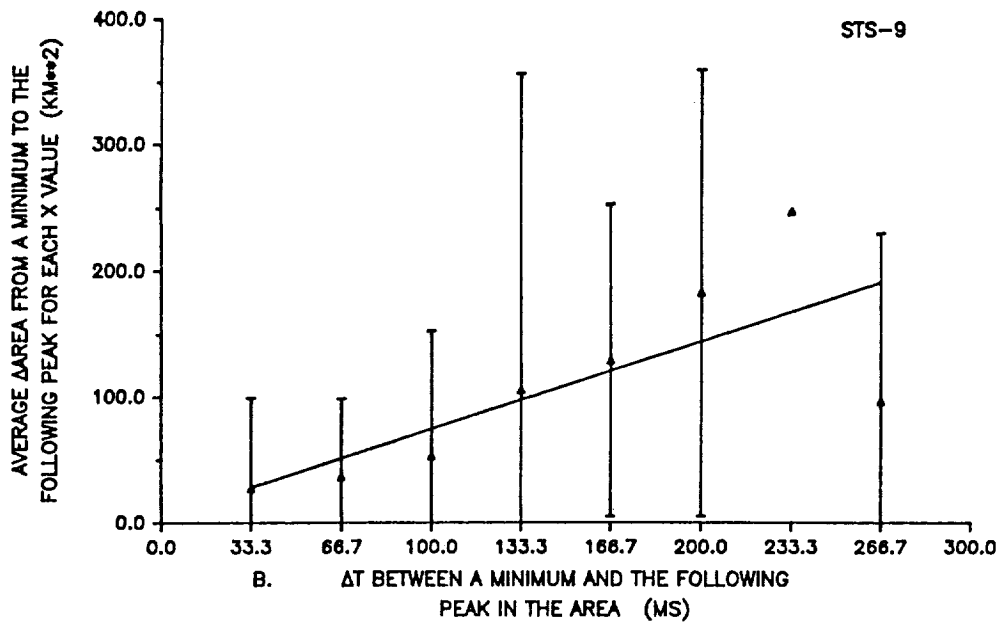
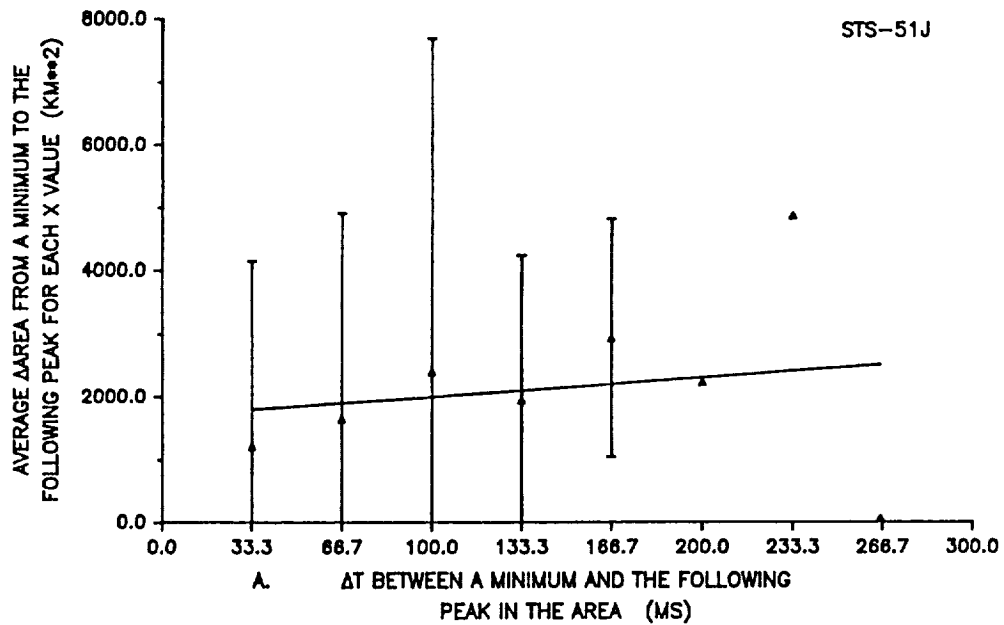
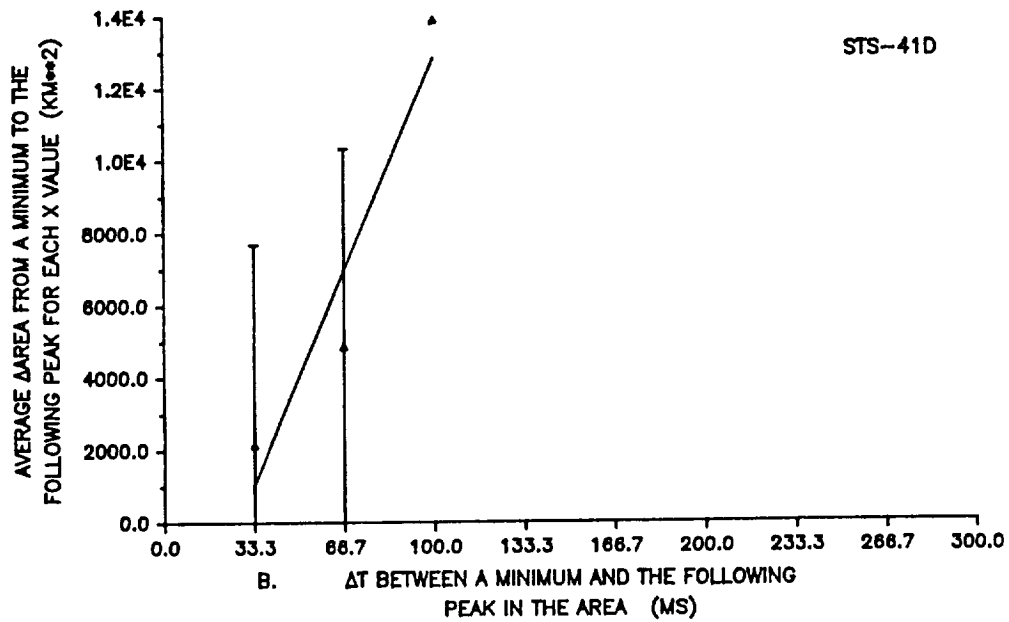
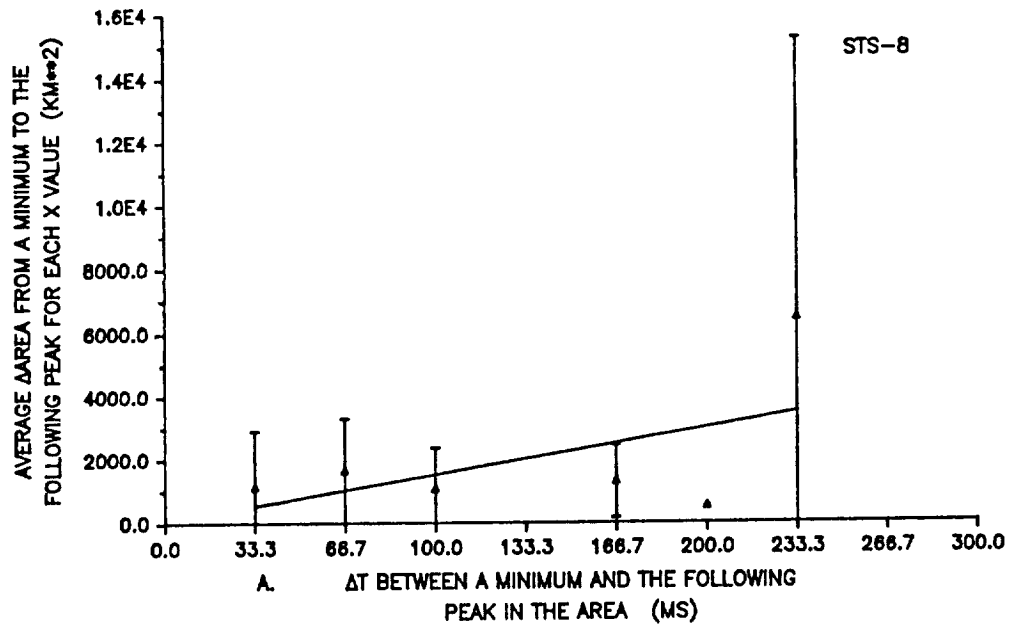


Figure 43A and B: Figure 43A is the same as Figure 38A, except that only the STS-41D data points are shown. Figure 43B is an enlargement of the region in 43A which is bounded by 6500 (km²) and 300ms. Note that none of the minimum to the following peak in the area curve time intervals lasted longer than 100 ms.



Figures 44A and B: Figure 44A shows the time interval from a minimum to peak in the area curve (ms), versus the average change in area (km²) over a given time interval, for the events of STS- 51J. The curve was calculated by a first order linear regression. The error bars indicate one standard deviation from the mean area. Figure 44B is the same as 44A, except that it is for the events of STS-9.



Figures 45A and B: Figures 45A and B are the same as Figure 44A, except that they are for the events of STS-8 and STS-41D, respectively.

interval over which the change in area occurred (Figure 44A). The correlation coefficient between these two variables is only 0.2 at a 0.40 level of significance. However, if the last three points which consisted of only one value before averaging are neglected, the curve gets much steeper and the correlation coefficient between the average change in the area and the change in time becomes 0.87 at a 0.05 level of significance.

A trend of increasing average change in the area with increasing time between a minimum and peak in the area curve is more obvious for the flashes of STS-9 (Figure 44B). The correlation coefficient between these two variables is 0.75 at a 0.05 level of significance.

The curves of the average change in the area versus time for both STS-8 and STS-41D show that as the time interval between a minimum and peak in the area increases, the average change in the area also increases (Figures 45A and B). The number of values of the change in the area before averaging was 10 times smaller for these two sets of data than that for STS-51J and STS-9. A small increase in the time period from a minimum to a peak in the area had a corresponding extremely large change in the average area, for the events of STS-41D. The correlation coefficients between these two variables are 0.43 and 0.95 for STS-8 and STS-41D, respectively. The correlation between the change in area and the time interval between a minimum and a peak is significant at a level of 0.20 and 0.15 for STS-8 and STS-41D, respectively.

5. The Bright Spot.

In some of the lightning events of STS-8, STS-9, and STS-51J, a small part of the illuminated region was brighter than the rest of the flash. This bright spot was visible in 16% of all the flashes, and remained visible for part or all of the duration of the flash. The size of this bright spot remained relatively constant. There were three flashes which had three bright spots, and four which had two bright spots. All of the flashes with multiple bright spots were on the STS-9 video.

On average, for all flashes, those with the very bright spot had a duration which was 74% longer than the average duration of those without a bright spot. The duration of the flashes with the bright spot ranged from 300 ms to 1433 ms. The average duration of the flashes with the bright spot was 57%, 70%, and 116% longer than the average duration of the flashes without a bright spot for STS-8, STS-51J, and STS-9, respectively.

The average maximum area of the bright spot flashes was compared to the average maximum area of those flashes without a bright spot. The average maximum area of the flashes with the bright spot was nearly equal to the average maximum area of the flashes without it, for all lightning events and for STS-51J events. However, the average maximum area of the flashes without the bright spot was much smaller than that of the flashes with the bright spot for the events of STS-8 and STS-9 (Table VI).

A comparison was made of the average time to the initial peak in area, for those flashes with the bright spot versus those without

Table VI: Some characteristics of flashes which had a very bright spot.
 "With" refers to the average values for flashes with the
 bright spot, and "Without" refers to the average values for
 flashes without the bright spot.

Flight	Number of flashes with the bright spot	Average duration (ms)		Average largest area (km ²)		Average time to first peak in the area curve (ms)	
		with	without	with	without	with	without
STS-8	10	680	432	5395	1378	90	84
STS-9	29	583	270	257	28	122	74
STS-51J	12	675	398	2928	2617	69	53
All Flashes	51	626	358	1893	1868	104	60

it. The average time to the initial peak in area was very similar for the STS-51J and STS-8 flashes with and without the bright region. This time interval for all flashes together, and for the STS-9 flashes was approximately 70% larger for those flashes with the bright spot. Thirty-five percent of the flashes with the bright spot had a time to the initial peak in area that was greater than 100 ms. These 18 flashes constitute approximately 42% of all the flashes, (those with and without the bright spot), whose time to the initial peak in area was greater than 100 ms. A summary of the characteristics of the flashes with the very bright spot is shown in Table VI.

6. Simultaneous Lightning Events.

Flashes which occurred simultaneously (ie. within the same video frame), were seen in the STS-41D, STS-51J, and STS-9 videos. The number of coincident flashes ranged from two to six in a given video frame. Each simultaneous flash was categorized by the maximum number of flashes which it appeared with at any given time. For example, flashes 1, 2, and 3 of STS-9 occurred together. Flash 1 lasted longer than flashes 2 and 3, and flash 4 then appeared towards the end of the lifetime of flash 1. Therefore, flashes 1, 2, and 3 would each be recorded as appearing with two other flashes, but flash 4 would be recorded as existing simultaneously with one other flash. By using this method, each simultaneous flash was counted only once.

The distance between the coincident flashes was measured on the first frame in which both flashes appeared together. If there

were more than two flashes, the distance was measured from each flash to the nearest coincident flash. The distance between simultaneous flashes ranged from 0.5 km to 360.0 km. The distance between flashes was divided into 10 km intervals and plotted with the number of times a given distance between a pair of flashes occurred (Figure 46). 38% of the values of the distance between two simultaneous events fell into the 0 km - 10 km interval. As the distance between the coincident flashes increased, the number of values in a given 10 km interval decreased rapidly. 84% of the data fell in the interval between 0 km and 130 km.

The average distance between two lightning events, for all flashes, was 60.0 km. The median value, however, was 24 km, reflecting the fact that a large portion of the data fell between 0 and 40 km. The average distance between the simultaneous flashes for each flight was 100 km, 14 km, and 7 km for STS-51J, STS-41D, and STS-9, respectively.

For all simultaneous events, the average time interval between the appearance of two consecutive simultaneous flashes was 190 ms. All but one of the values of this time interval had a duration of 433 ms or less. In one case, the time between two consecutive simultaneous flashes lasted 933 ms (in the STS-9 video). On average, this time interval lasted 245 ms, 17 ms, and 124 ms for the consecutive simultaneous flashes of STS-51J, STS-41D, and STS-9, respectively. More than half of the values of this interflash time period lasted 200 ms or less for all simultaneous flashes, as well as for those simultaneous flashes of STS-41D, STS-51J, and STS-9.

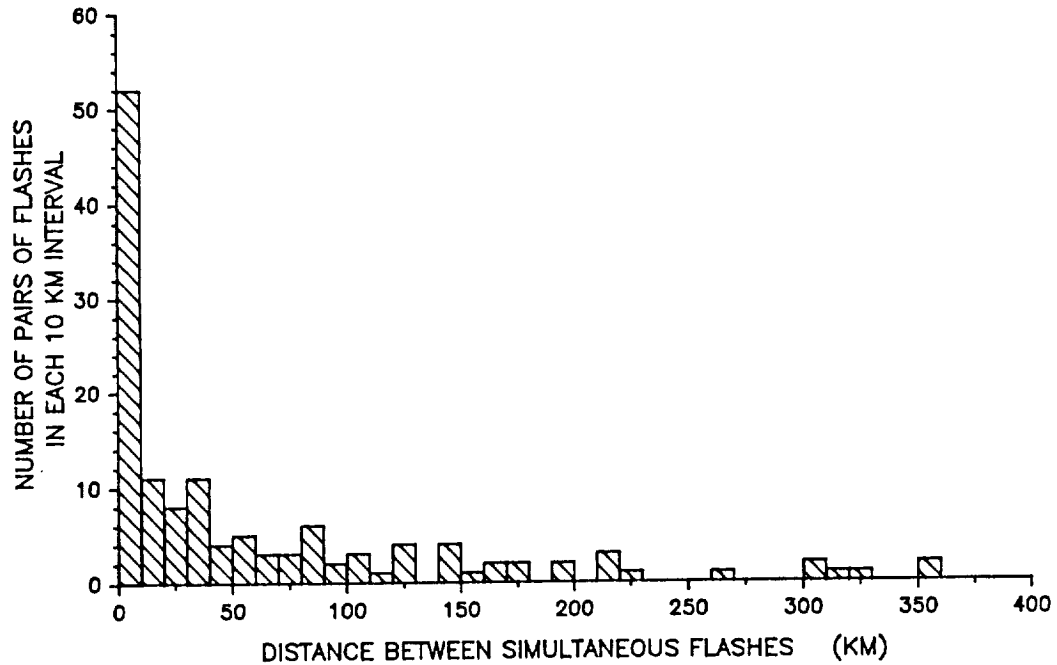


Figure 46: The distance between two simultaneous events (km), versus the number of pairs of simultaneous events a given distance apart. The number of events has been summed for each 10 km interval. The distance between two events was measured on the initial video frame in which both flashes appeared. When more than two events were simultaneous, the distance was measured between the two closest events.

The percent of the lightning events which occurred alone, or simultaneously with one and up to five other flashes, is shown in Figure 47, for all flashes, and for each flight. 64% of all flashes could be classified as simultaneous events. The events of STS-9 had the greatest percentage of simultaneous flashes. 37%, 65%, and 74% of the flashes could be classified as simultaneous for STS-41D, STS-51J, and STS-9 respectively.

Figure 48 shows the number of lightning events which occurred alone or simultaneously with one to five other events. At five and six flashes occurring together, the symbols for STS-9 and all flashes overlap. Most of the time, only two events were time coincident. There were only a small number of events with 4, 5, and 6 flashes appearing simultaneously. For all flashes and for those of STS-9, the number of flashes which appeared alone was nearly equal to the number of flashes which occurred with one other flash.

The percent of simultaneous flashes which appeared in groups of two to six flashes is shown in Figure 49. Note that there is no data with an abscissa value of one because a single flash present in time is not simultaneous with any other flashes. The data points of all flashes, STS-51J, and STS-9 overlap at four flashes occurring simultaneously. There was only one occurrence of simultaneous flashes in STS-41D, when three flashes were coincident. More than half of the simultaneous flashes in STS-51J and for all flashes occurred with only one other flash. Only a very small percent of the coincident flashes occurred with more than two other flashes.

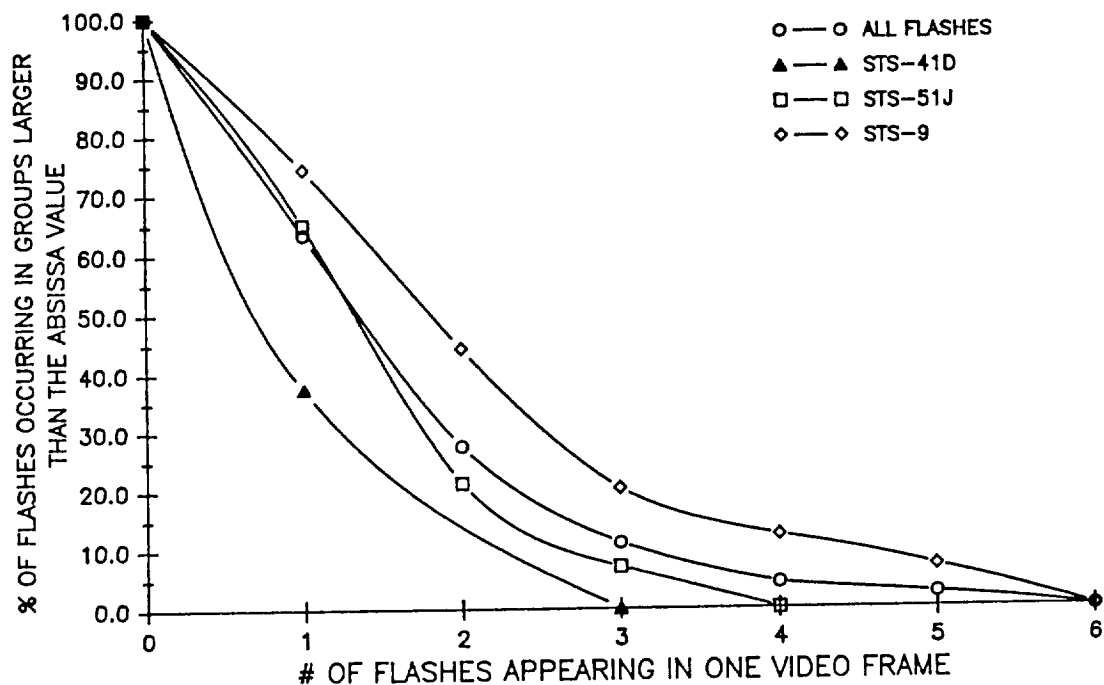


Figure 47: The number of lightning events appearing at one time, versus the percent of events which appeared in a group larger than any given number of events. The curve was calculated by a cubic spline. The curve is shown for all flashes, as well as for the events of STS-41D, STS-51J, and STS-9. At 5 and 6 flashes appearing in a video frame, the symbols for STS-9 events and all events overlap.

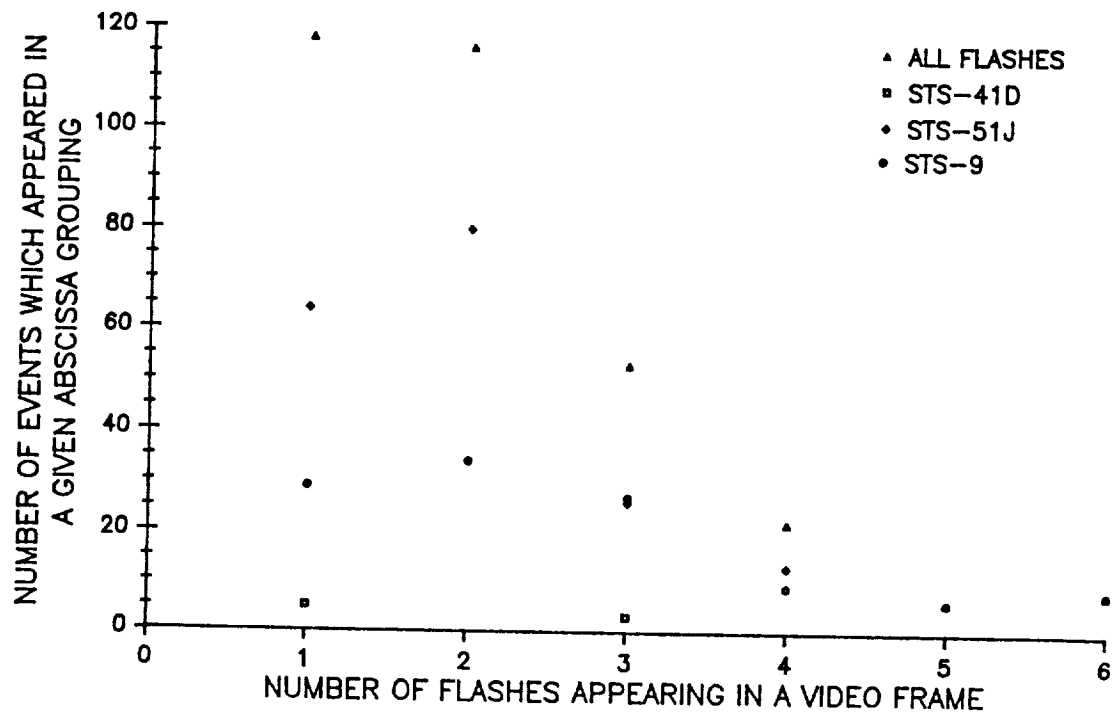


Figure 48: The number of events appearing together in a video frame versus the number of flashes which appeared in a given grouping. This is shown for all events together, as well as for the events of STS-9, STS-41D, and STS-51J.

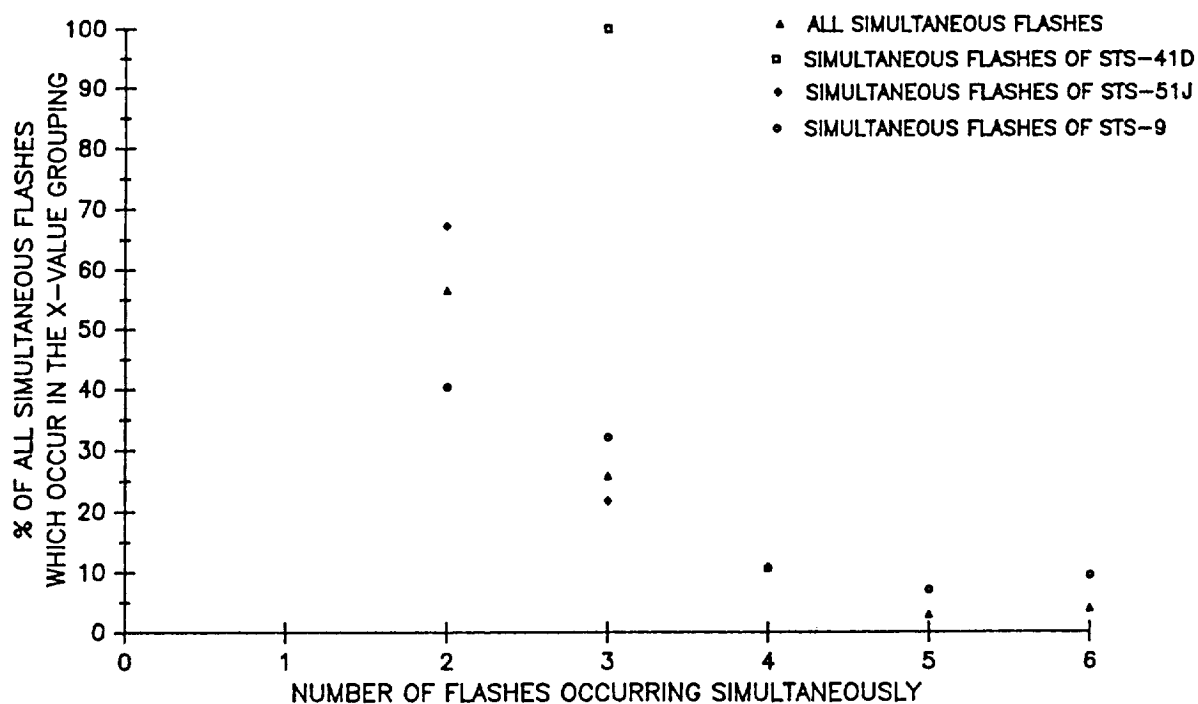


Figure 49: Figure 49 shows the percent of all simultaneous events which occurred in a group of coincident events, of a given size. There aren't any data points for the x-value of 1, because one event appearing alone is not simultaneous with any other event. At four flashes occurring simultaneously the data points for STS-9, STS-51J, and all flashes overlap.

If a breakdown process was occurring between simultaneous flashes, its rate of propagation could be calculated by dividing the distance between the two flashes by the time interval, from the appearance of the first flash to that of the second event. The average speed of such a process would be $4.6 \times 10^5 \text{ msec}^{-1}$, for all flashes. On average, this breakdown process between two coincident flashes in STS-41D, STS-51J, and STS-9 would have a speed of $4.7 \times 10^5 \text{ msec}^{-1}$, $7.3 \times 10^5 \text{ msec}^{-1}$, and $0.98 \times 10^5 \text{ msec}^{-1}$, respectively. 23% of the flash pairs in STS-51J would have a breakdown propagation rate on the order of 10^6 msec^{-1} . This large of a value of the propagation of a breakdown process between two flashes was not found in the other two videos in which flashes appeared simultaneously.

7. The Area Curves.

The fluctuations in the area of the illumination were plotted over the lifetime of each flash. Even when several lightning events were plotted together on one graph, there were 164 graphs of area versus time. In the interest of conserving space, 33 graphs showing both the average and anomalous characteristics of the flashes from each video were chosen.

a) The big ones.

Figures 50 through 56 show the change in the area of the illumination over the duration of the flash, for the nine flashes whose maximum area exceeded 12000 km^2 . The plot of the area versus time, for the first five flashes of STS-41D, includes the area

curves of three of the nine largest events (Figure 50). The dimensions of the major and minor axes, when the maximum area was attained by flashes 2, 3, and 4, were approximately 200 km x 130 km, 130 km x 135 km, and 120 km x 150 km, respectively. Flash 2 reached its maximum area on the first video frame in which it appeared (33 ms), while flashes 3 and 4 reached their maximum area at 100 ms and 133 ms, respectively. All three flashes maintained an area greater than 12000 km^2 for at least 133 ms. Flash 4 has four peaks in its area over the duration of the flash. This is the maximum number of peaks in the area found for any STS-41D event. None of the flashes shown in Figure 50 were coincident with any other flashes. Events 1 and 5 are more typical of the average flash from STS-41D in size, duration, and number of peaks in the area. A rate of growth of 10^6 msec^{-1} from the initial to the largest dimension occurred along the minor axis of flashes 2 and 5, and along the major axis of flashes 2 and 3.

Flash 53 from STS-51J had maximum dimensions of 345 km x 85 km (Figure 51). It occurred simultaneously with flash 57. These two flashes were 95 km apart. Both flashes appeared at the same time, and flash 56 lasted approximately 166 ms longer than flash 57. Both flashes had duration which were longer than that of the average STS-51J flash. Flash 56 differs from the large flashes of STS-41D in that its maximum area occurs near the middle of its lifetime. The large size of this event is maintained for a much shorter time period than for the large events of STS-41D. The maximum area of flash 57 is more typical of the lightning events

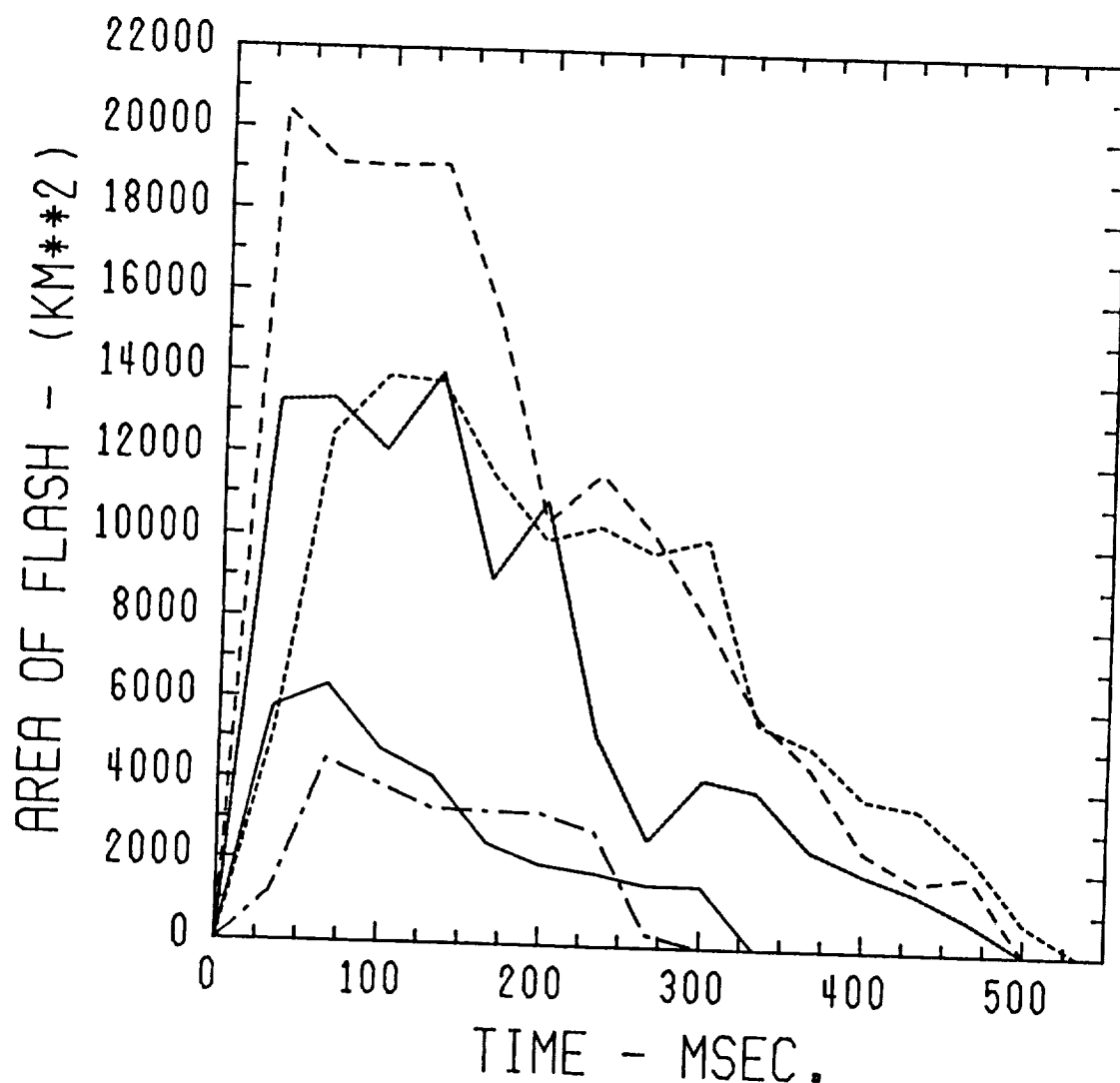


Figure 50: This figure shows the fluctuations in the area of a flash over its lifetime, for the first five events from STS-41D. These events were not simultaneous. Events 2, 3, and 4 are three of the nine events whose maximum area exceeded 10,000 km². (Flash 1: solid curve; Flash 2: long dash curve; Flash 3: short dash curve; Flash 4: dotted curve; Flash 5: dash-dot curve).

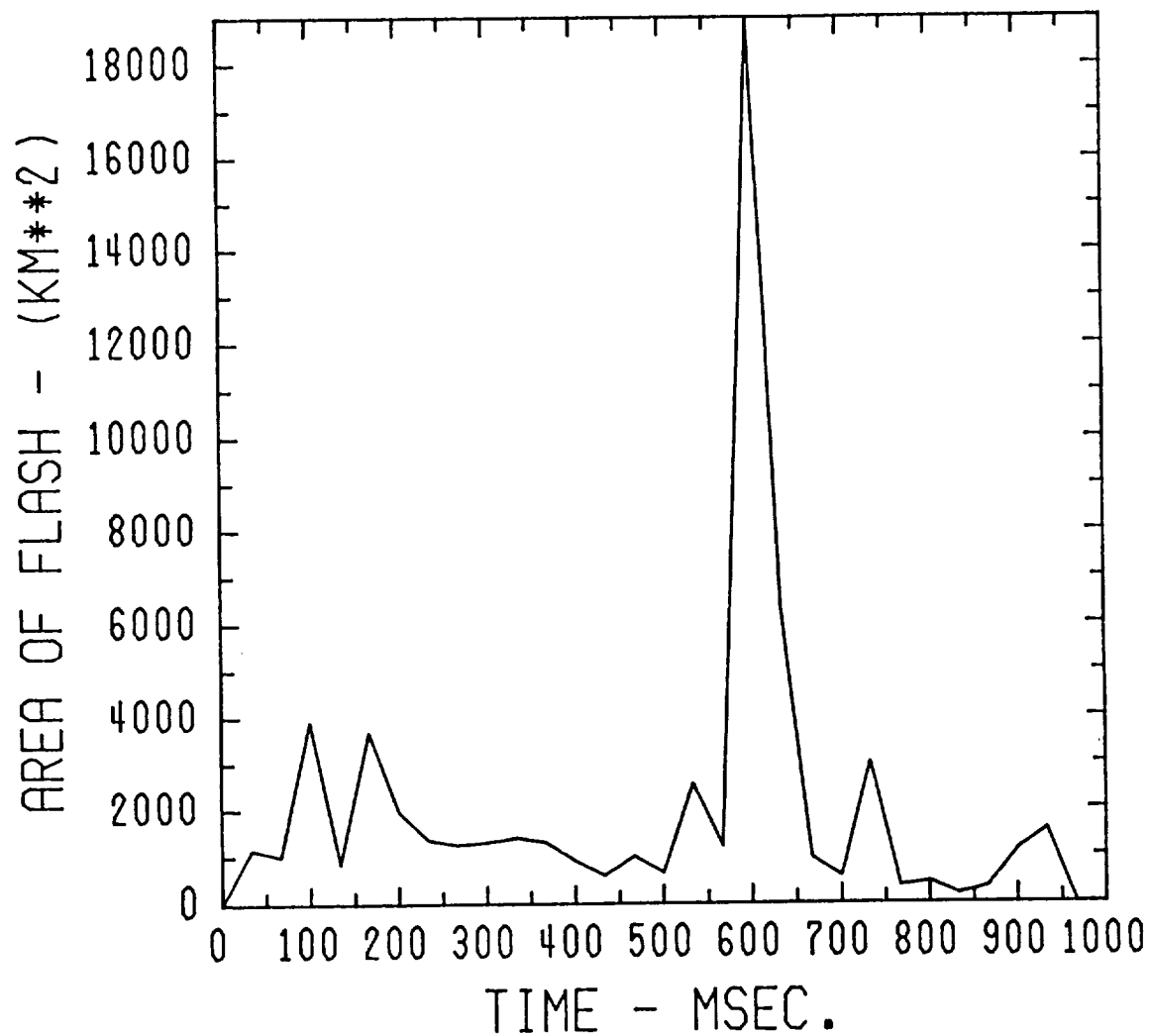


Figure 51: This figure shows the fluctuations in the area of a flash over its lifetime, for flashes 56 and 57 of STS-51J. These two simultaneous events were 95 km apart. (Flash 57: solid curve; Flash 58: broken curve).

appearing in the STS-51J video.

Flash 70 of STS-51J lasted 966 ms, and reached its peak area at 64% of its total duration (Figure 52). It is one of a small group of flashes whose duration was greater than 800 ms. Its largest dimensions were 240 km x 100 km. As in the previous figure, these large dimensions occurred over a short time period. There are ten peaks in the area over the duration of flash 70.

Flash 84 of STS-51J is a very unique lightning event (Figure 53). There are fourteen peaks in the area of the flash over its 1833 ms lifetime. Flash 84 had the longest duration and the greatest number of peaks of all 323 lightning events. Five of the fourteen peaks in area were larger than 12000 km². This particular flash also had the largest ratio of the peak area to the initial area, 255:1. The maximum area of this flash was 335 km x 130 km, and occurred at 67% of the total duration of the flash. Five other coincident flashes began and ended within the lifetime of flash 84. Near 800 ms and 1500 ms, there are three flashes existing at the same time. The distance between these simultaneous flashes is noted in Figure 53. Flash 87, which reached its peak area on its first video frame (33 ms), had a rate of growth of 10^6msec^{-1} from its initial to its largest dimensions along the major axis of the illumination.

Flash 134 of STS-51J was the largest of all the lightning events (Figure 54). This flash reached its maximum dimensions of 440 km x 110 km half way through its 933 ms lifetime. Two other very large peaks in the area preceded the maximum area. These

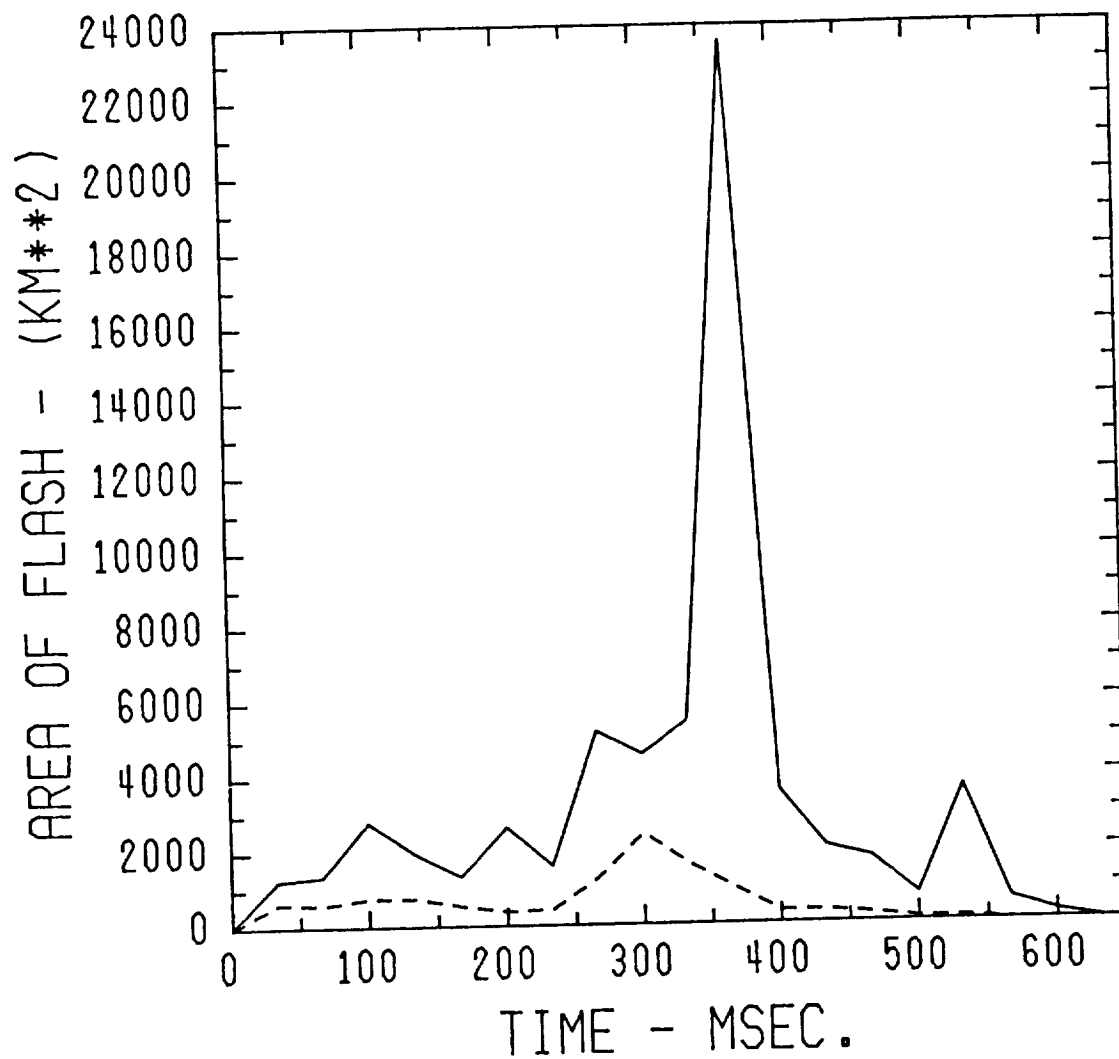


Figure 52: This figure shows the fluctuations in the area of a flash over its lifetime, for flash 70 of STS-51J.

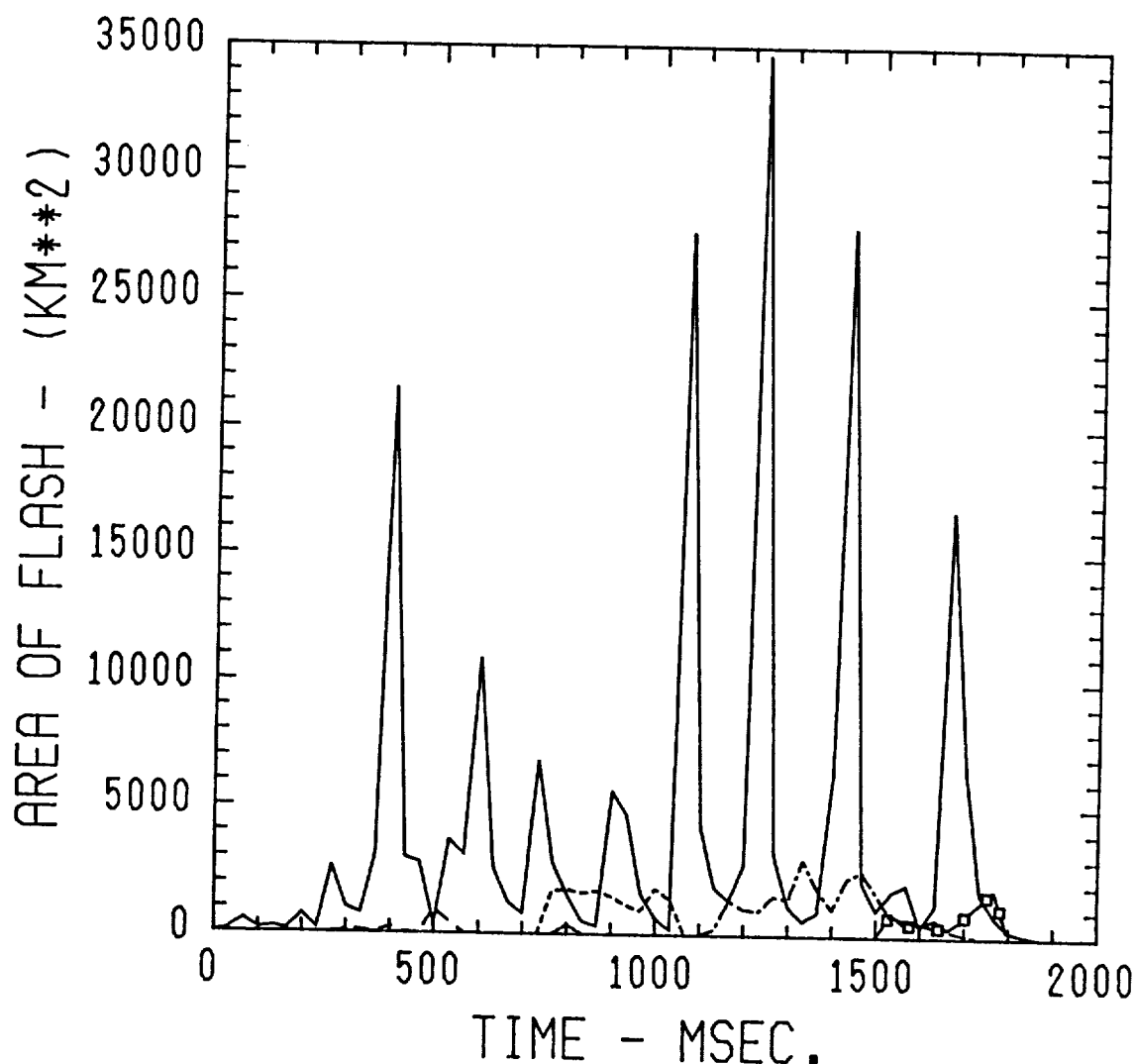


Figure 53: This figure shows the fluctuations in the area of a flash over its lifetime, for simultaneous flashes 84 through 89 of STS-51J. Events 84/85, 84/86, and 84/87 were 70 km, 5 km, and 210 km apart, respectively. Events 84/88 and 84/89 were 170 km and 110 km apart, respectively. Event 84 had the longest duration and largest number of peaks in the area curve, of all 323 flashes. (Flash 84: solid curve; Flash 85: long dash curve; Flash 86: short dash curve; Flash 87: dotted curve; Flash 88: dash-dot curve; Flash 89: dash-square curve).

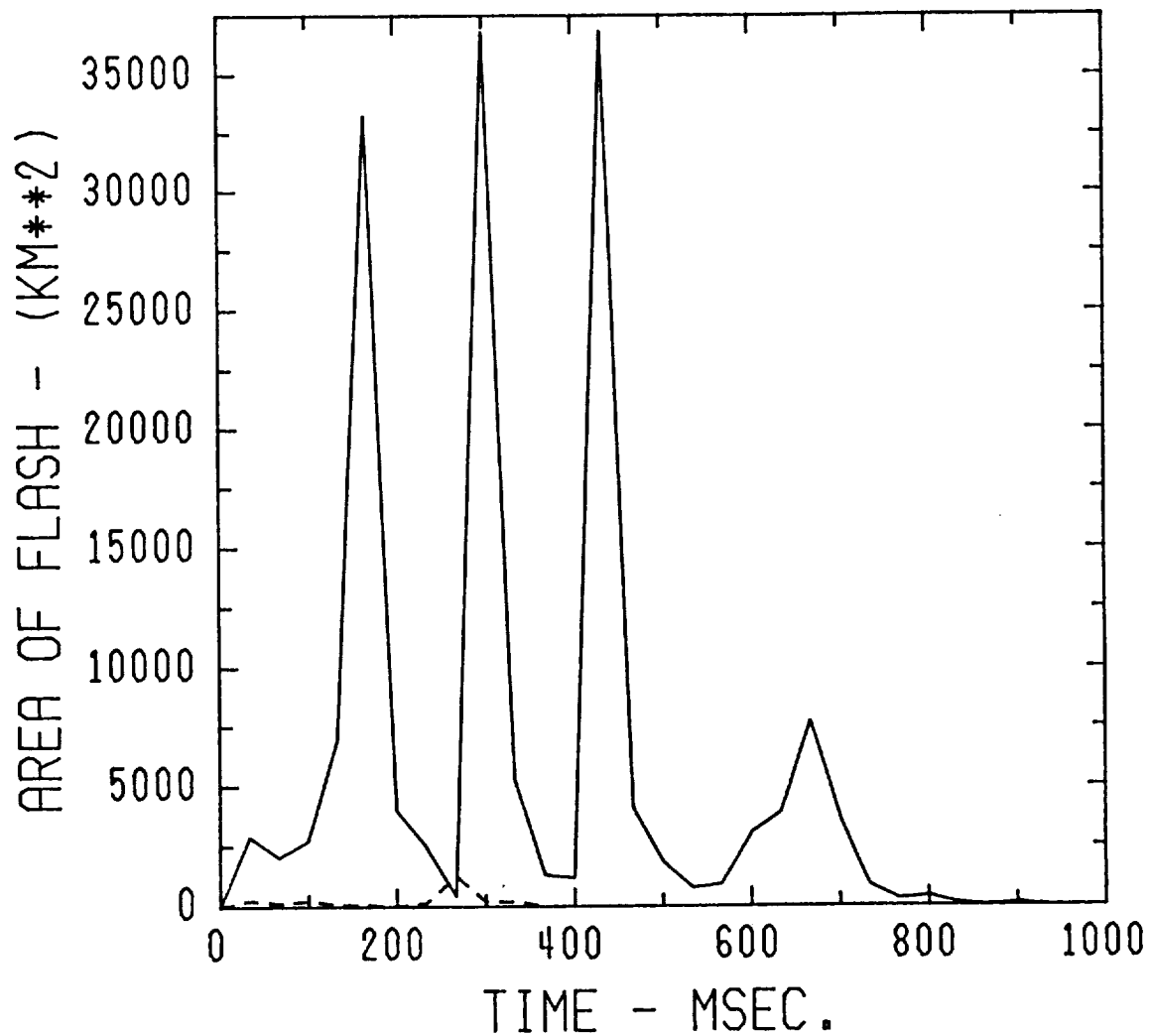


Figure 54: This figure shows the fluctuations in the area of a flash over its lifetime, for simultaneous events 134 and 135 of STS-51J. These two events were 100 km apart. Flash 134 was the largest of all 323 lightning events, with maximum dimensions of approximately 440 km x 110 km. (Flash 134: solid curve; Flash 135: broken curve).

three major peaks are separated by the same time interval. Flash 134 appeared simultaneously with flash 135. These two events were 100 km apart.

The largest lightning event on the STS-8 video was flash 2 (Figure 55). Flash 2 maintained an area of 12000 km^2 or larger for almost 100 ms. Its maximum dimensions of 165 km x 100 km were attained at 35% of the total duration of the flash. Note that the peaks in the area of flash 2 get successively smaller after 250 ms.

In Figure 55, flash 2 is contrasted with the first, third, fourth, and fifth lightning events of STS-8. These five flashes did not appear simultaneously. Note that the duration of flash 1 is 100 ms longer than that of flash 2, yet flash 1 is only 1/6 as large at its maximum extent. Flash 5 had the second smallest maximum area of all the STS-8 flashes. Flashes one through three lasted at least 100 ms longer than the average duration of all STS-8 lightning events. Flashes 4 and 5 had below average durations. The persistent bright spot that was mentioned in section 3.5, was visible in flashes 1, 2, and 3.

Flash 10 of STS-8 reached its maximum dimensions of 130 km x 120 km at 35% of its total duration. It is shown along with flashes 6 through 9 (Figure 56). Both flashes 9 and 10 had the longest duration of all the STS-8 lightning events. Flash 10 also had the greatest number of peaks in the area curve of all STS-8 flashes.

Flash 7 is the only STS-8 lightning event that reached its peak area on its initial frame (33 ms). This flash exhibited a rate of growth, to its maximum dimensions, of 10^6 msec^{-1} along both the

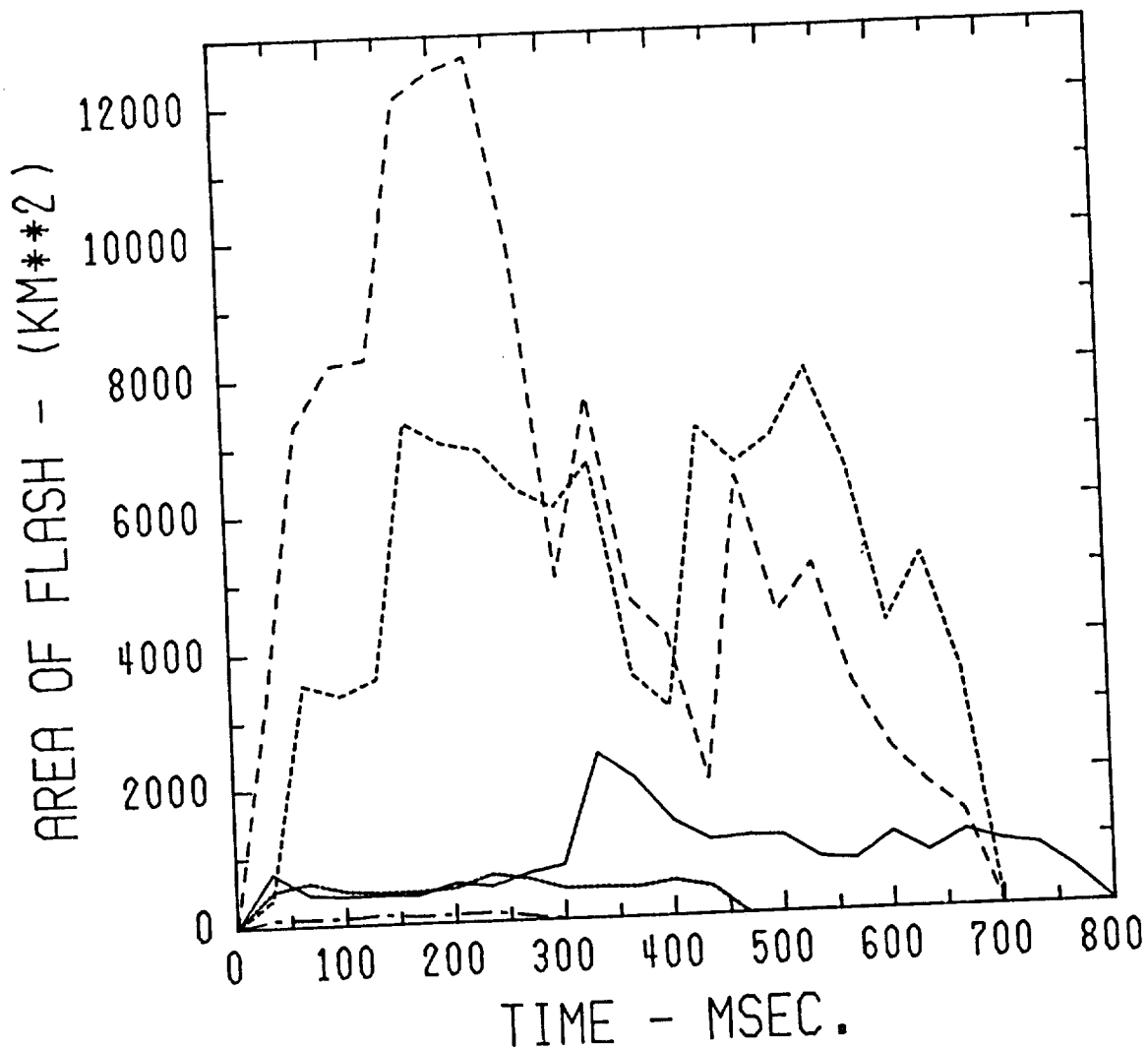


Figure 55: This figure shows the fluctuations in the area of a flash over its lifetime, for events 1 through 5 of STS-8. These events were not simultaneous. Flash 2 was the largest of all STS-8 events. Flashes 1 - 3 had the bright spot that was mentioned in the text. (Flash 1: solid curve; Flash 2: long dash curve; Flash 3: short dash curve; Flash 4: dotted curve; Flash 5: dash-dot curve).

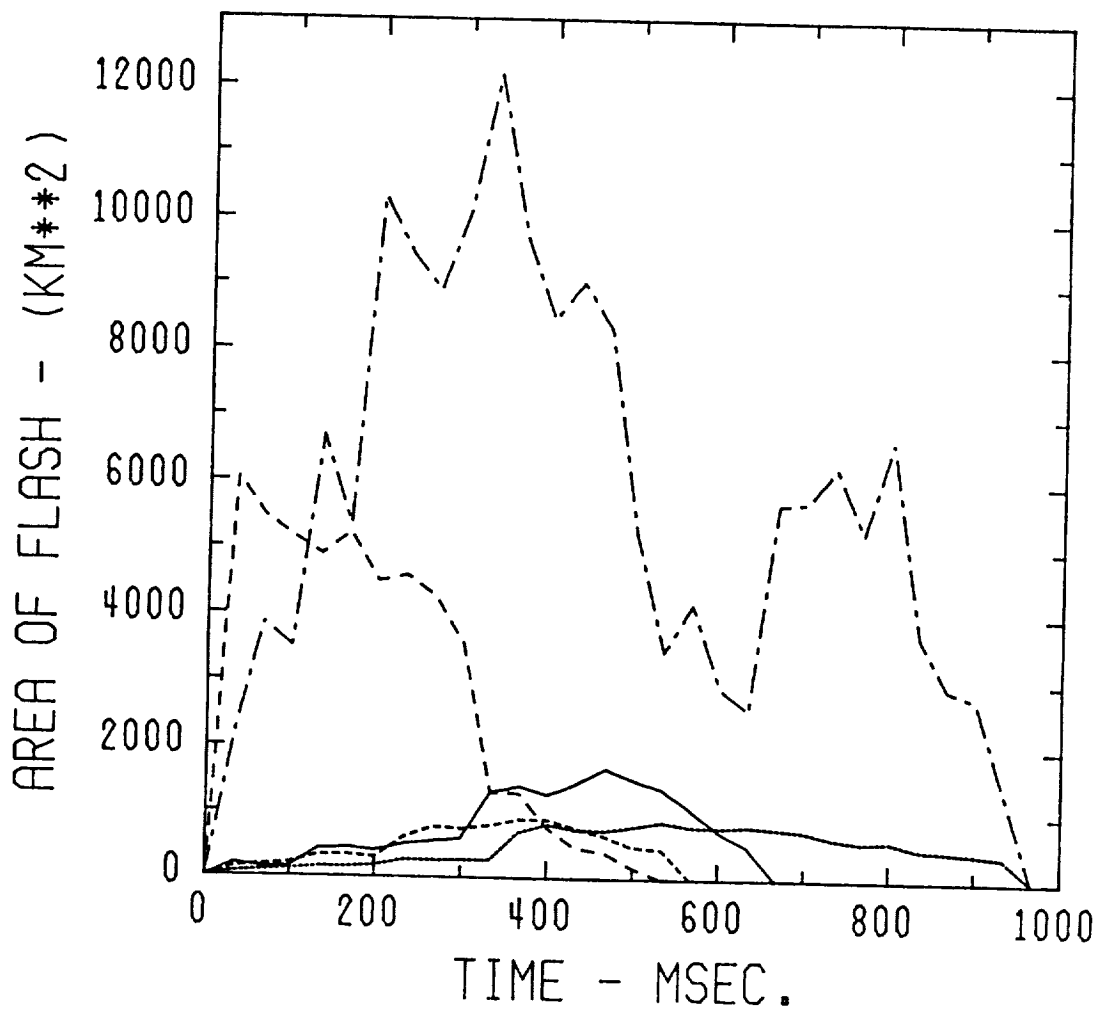


Figure 56: This figure shows the fluctuations in the area of a flash over its lifetime, for events 6 through 10 of STS-8. These events were not simultaneous. Events 9 and 10 had the longest duration of all STS-8 events. The bright spot appeared in events 6, 9, and 10. (Flash 6: solid curve; Flash 7: long dash curve; Flash 8: short dash curve; Flash 9: dotted curve; Flash 10: dash-dot curve).

major and minor axis of the flash. The duration, and number of peaks in the area of flashes 7 and 8 are typical for an average STS-8 flash. The bright spot was visible in flashes 6, 9, and 10.

b) Periodic peaks.

Flash 84 of STS-51J (Figure 53) is one of a small group of events whose peaks in the area curve occur periodically. Another example of this type of event is flash 11 of STS-51J, shown in Figure 57. The interpeak interval is constant for the first five peaks of flash 11. Flashes 11 and 12 occurred simultaneously and were 260 km apart. Flash 12 reached its only peak on its initial video frame. The rate of growth from the initial to the largest extent of flash 12 was on the order of 10^6 msec^{-1} along the major axis of the flash.

c) The area curves of flashes with average and below average size and duration.

The area curves of a series of lightning events from STS-9 appear in Figures 58 through 61. Events 16 through 20 of STS-9 did not occur simultaneously, but were put on the same graph to illustrate the variation in the size and duration of the STS-9 lightning events (Figure 58). Flashes 16 and 18 have the largest and smallest maximum areas, respectively, of all the STS-9 flashes. All of these events, except for flash 18, had a bright spot in their illumination. Flash 20 is typical of an average STS-9 flash in duration, maximum area, and number of peaks in the area. Flashes 16 and 20 are examples of the 13% of all flashes whose first peak in area occurred after 100 ms.

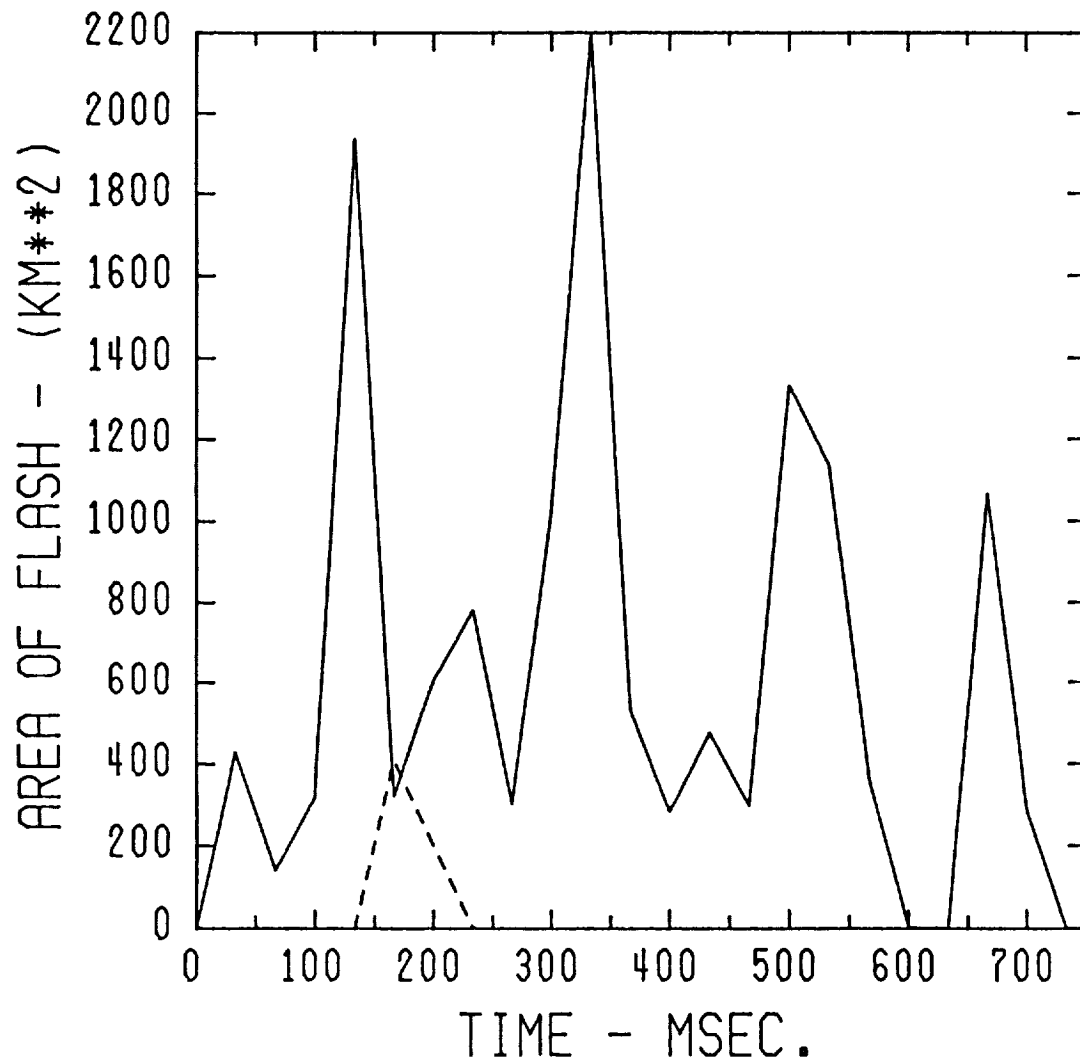


Figure 57: This figure shows the fluctuations in the area of a flash over its lifetime, for simultaneous events 11 and 12 of STS-51J. These two events were 260 km apart. Notice the almost constant time interval between the peaks in the area curve of flash 11. (Flash 11: solid curve; Flash 12: broken curve).

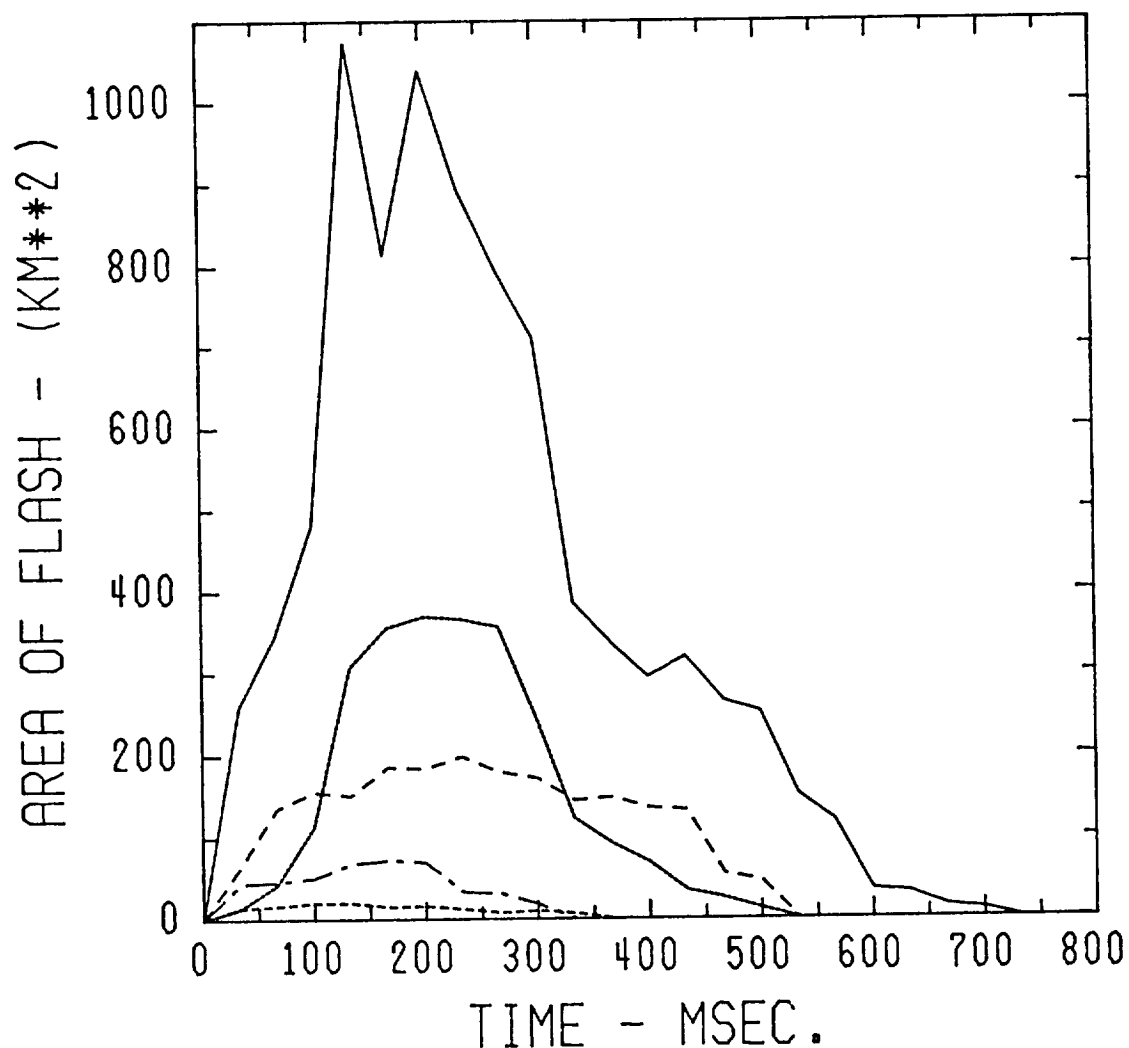


Figure 58: This figure shows the fluctuations in the area of a flash over its lifetime, for events 16 through 20 of STS-9. These events were not simultaneous. Events 16 and 18 have the largest and smallest maximum area of all STS-9 events, respectively. (Flash 16: solid curve; Flash 17: long dash curve; Flash 18: short dash curve; Flash 19: dotted curve; Flash 20: dash-dot curve).

Flashes 86 through 89 of STS-9 are representative of events which are below average in their size and duration (Figure 59). These four flashes also show a variety in the number of peaks in the area curve per flash. Two simultaneous flashes from STS-9 are shown in Figure 60. Flashes 5 and 6 were 2 km apart. There were two bright spots appearing in flash 5, and one in flash 6. Flash 5 had a maximum area and number of peaks in the area curve which are typical of the average STS-9 flash. Of all the STS-9 events, flash 5 had the greatest value of the ratio of the maximum area to the initial area, 113:1. The difference in the shape of these two curves is quite apparent. The major peaks in the area of flash 5 get increasingly larger, while flash 6 exhibits a large peak at the beginning and end of its lifetime.

The longest lasting event of STS-9, flash 63, is contrasted with flash 50, whose duration is typical of an average STS-9 lightning event (Figure 61). These two flashes did not occur simultaneously. Flash 63 reached its first peak in area beyond 100 ms. Of all the STS-9 events, this flash had the most peaks in area over its lifetime.

Figures 62 through 64 show the change in area over time for more of the lightning events of STS-51J. Flashes 1 through 4 (Figure 62) were not time coincident. They are plotted together to show the variation in size, duration, and number of peaks in the area of the flashes of STS-51J. The longest lasting of these four events, flash 3, had a duration nearly equal to the average duration of the STS-51J flashes.

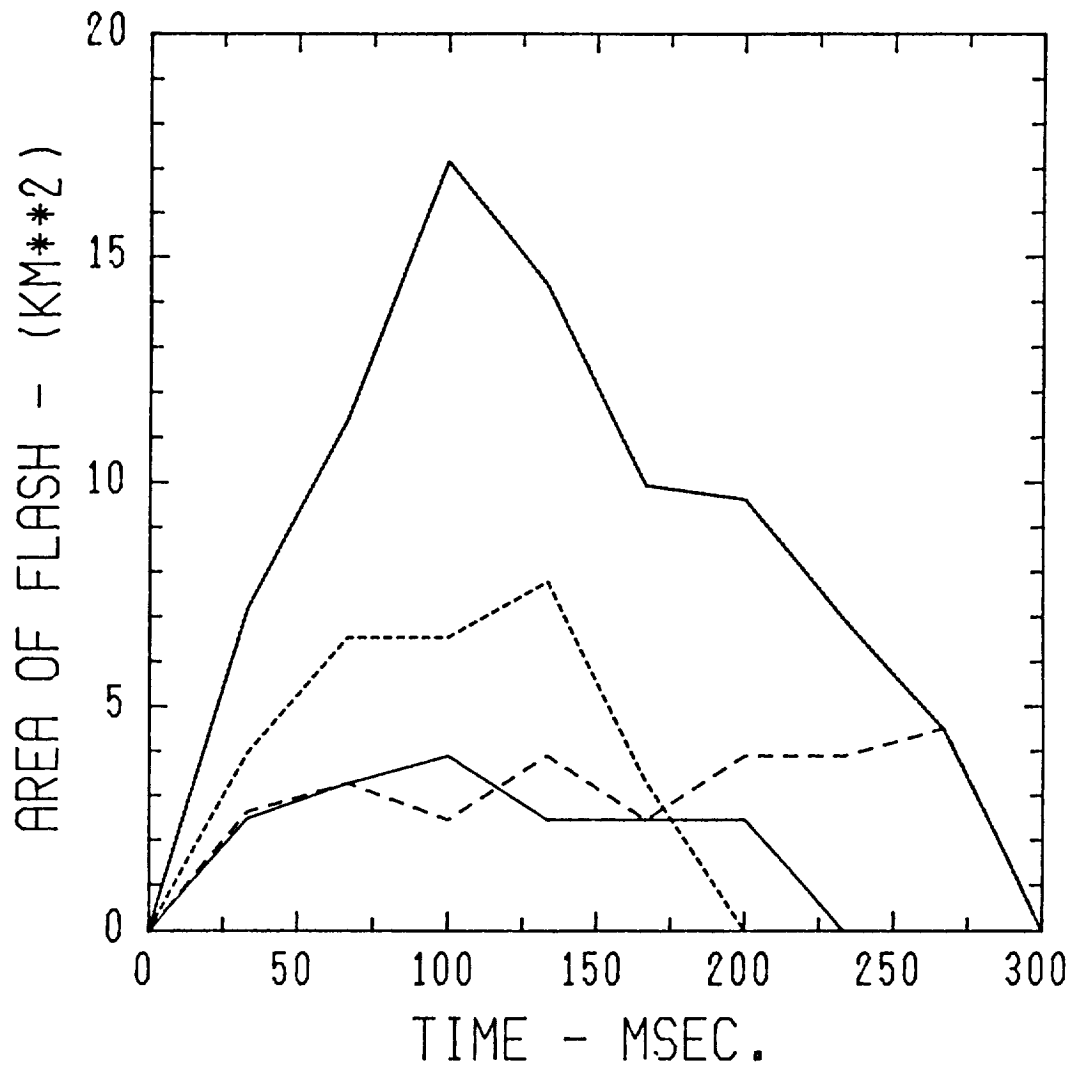


Figure 59: This figure shows the fluctuations in the area of a flash over its lifetime, for events 86 through 89 of STS-9. These events were not simultaneous. Flashes 86 through 89 were some of the smallest STS-9 events. They also had some of the shortest durations of all STS-9 flashes. Note the variation in the number of peaks in the area curves. The curves of flashes 87 and 88 overlap during the last 33ms. (Flash 86: solid curve; Flash 87: long dash curve; Flash 88: short dash curve; Flash 89: dotted curve).

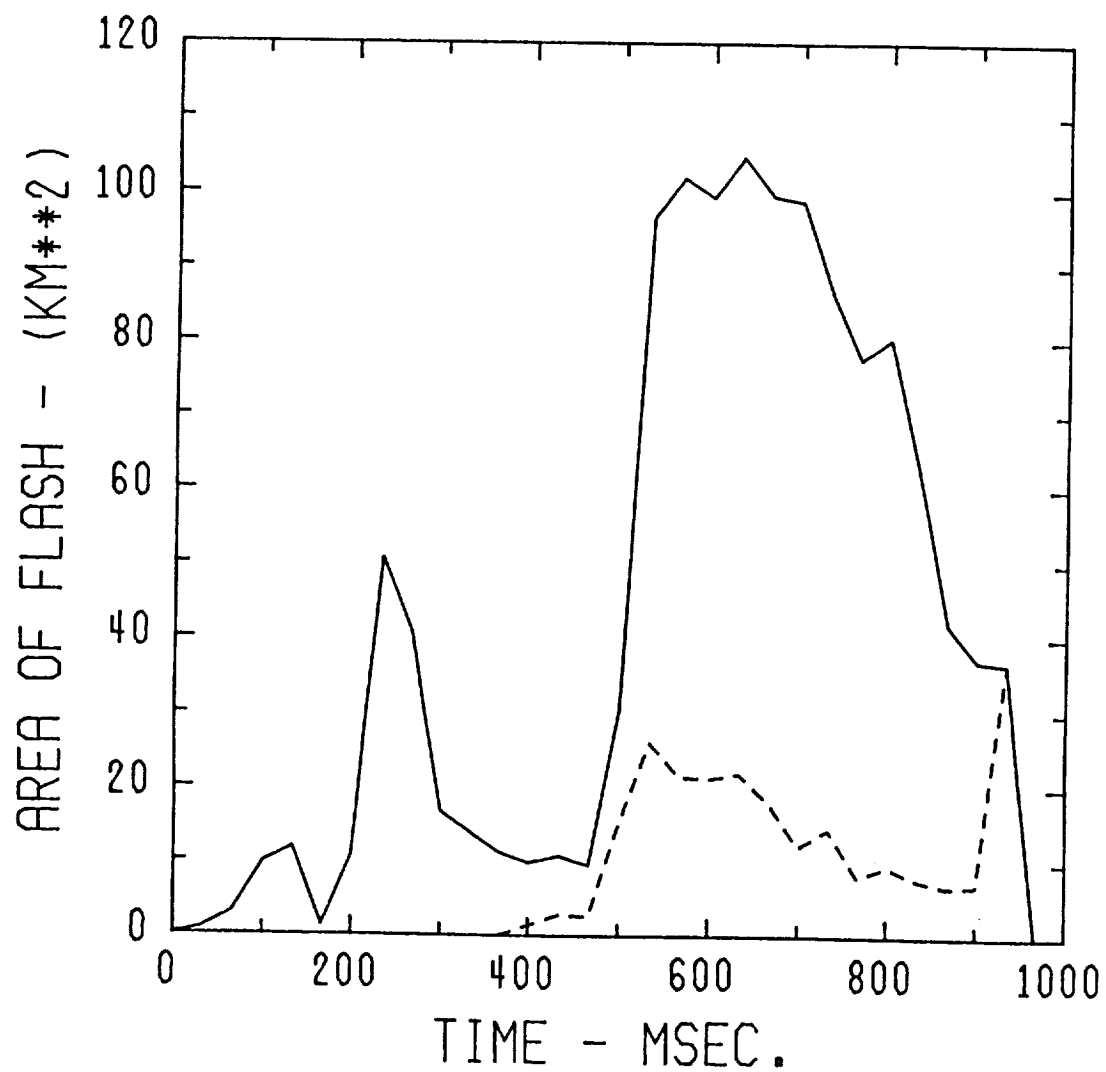


Figure 60: This figure show the fluctuations in the area of a flash over its lifetime, for simultaneous events 5 and 6 of STS-9. These two events were 2 km apart. Flash 5 had two bright spots, while flash 6 had one. (Flash 5: solid curve; Flash 6: broken curve).

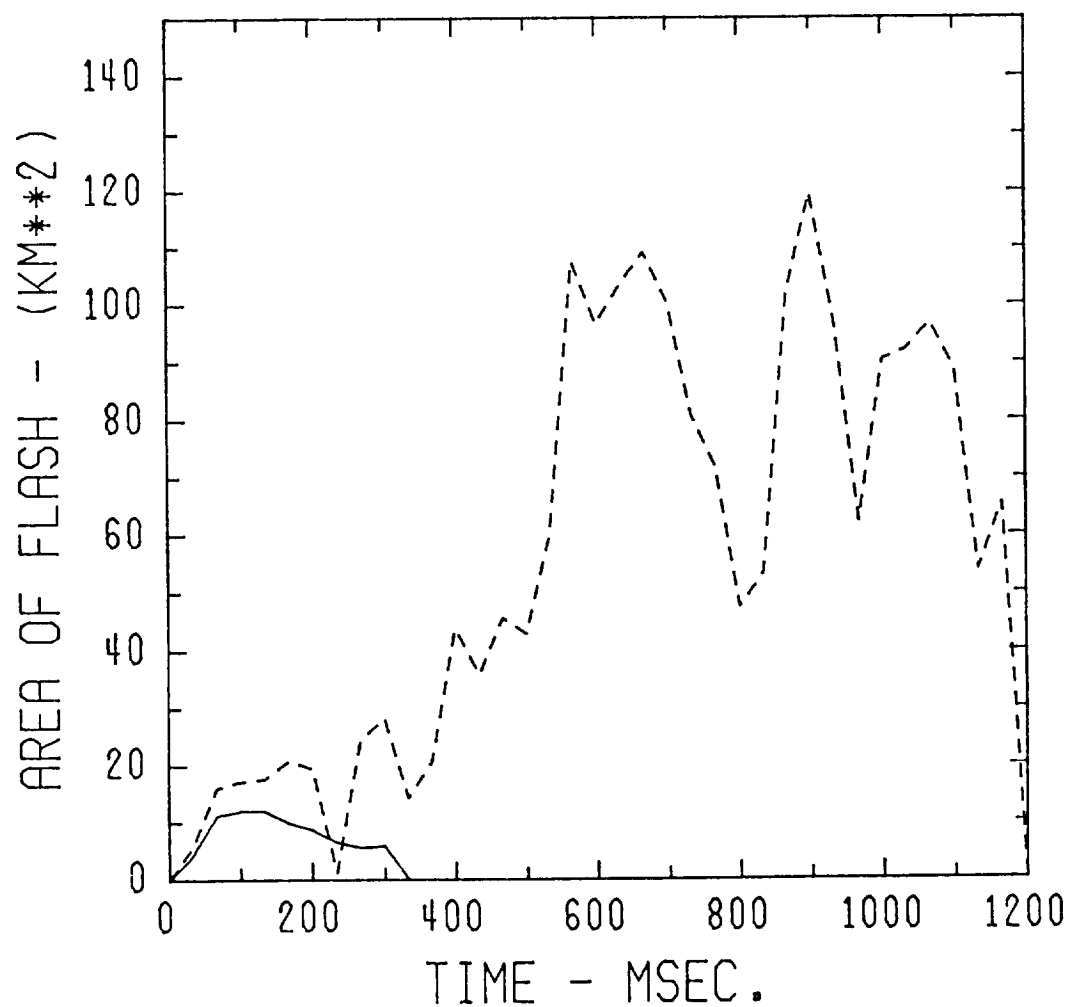


Figure 61: This figure shows the fluctuations in the area of a flash over its lifetime, for events 50 and 63 of STS-9. These two events were not simultaneous. Flash 63 had the longest duration, and most peaks in the area curve of all STS-9 events, while flash 50 had a duration which is typical of the average STS-9 event. (Flash 50: solid curve; Flash 63: broken curve).

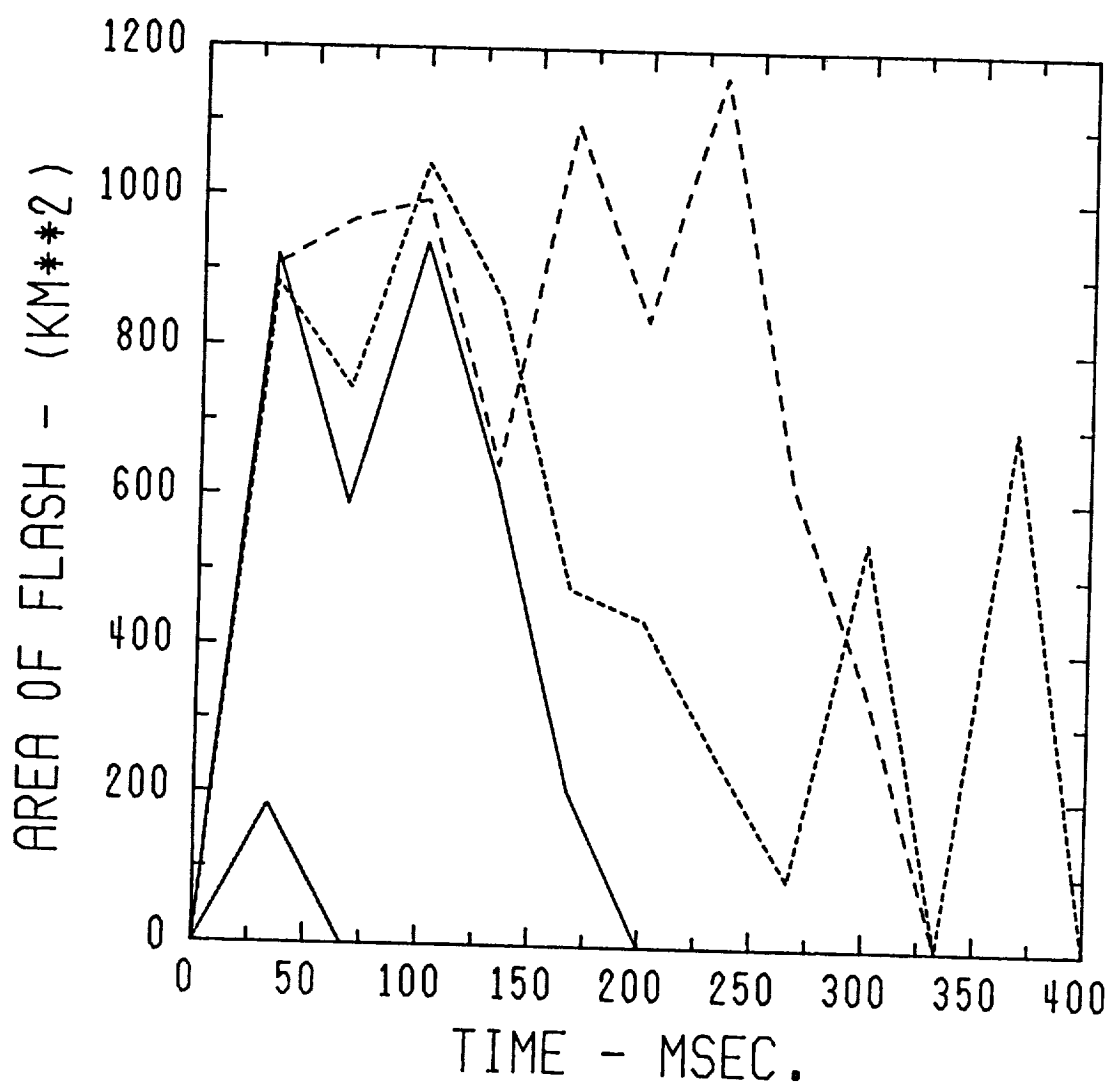


Figure 62: This figure shows the fluctuations in the area of a flash over its lifetime, for events 1 through 4 of STS-51J. These events were not simultaneous. They illustrate the variation in the size, duration, and number of peaks in the area curve of the STS-51J events. (Flash 1: solid curve; Flash 2: long dash curve; Flash 3: short dash curve; Flash 4: dotted curve).

Flashes 142 through 144 are examples of STS-51J events with a short duration and only a few peaks in the area (Figure 63). The time interval to the maximum area is shorter than the subsequent time interval in which the area decreases, for all three flashes. All three of these flashes reached their maximum area on the first video frame in which they appeared. All three of these flashes exhibited a rate of growth from the initial to the largest dimensions of 10^6 msec^{-1} along their major axis. Flashes 142 and 143 also had this same rate of growth along their minor axis.

Flashes 43 and 44 occurred simultaneously and were 130 km apart (Figure 64). Flash 44 appeared in the last 66 ms of the lifetime of flash 43. Flash 43 is typical of an average STS-51J flash with four peaks in its area, and a 433 ms duration. Flash 44 lasted almost twice as long as flash 43 and had almost twice as many peaks.

d) The area curves of simultaneous events.

A series of simultaneous flashes appear in Figures 65 through 71. These flashes were chosen to show the variation in the distance between two simultaneous flashes, and in how much of the lifetime of one flash overlaps that of another. As previously stated, the distance between flashes was measured from one flash to the nearest time coincident flash, on the first video frame in which they appeared. The area curves of these coincident flashes are plotted over time, with respect to the appearance of the first simultaneous flash in the group.

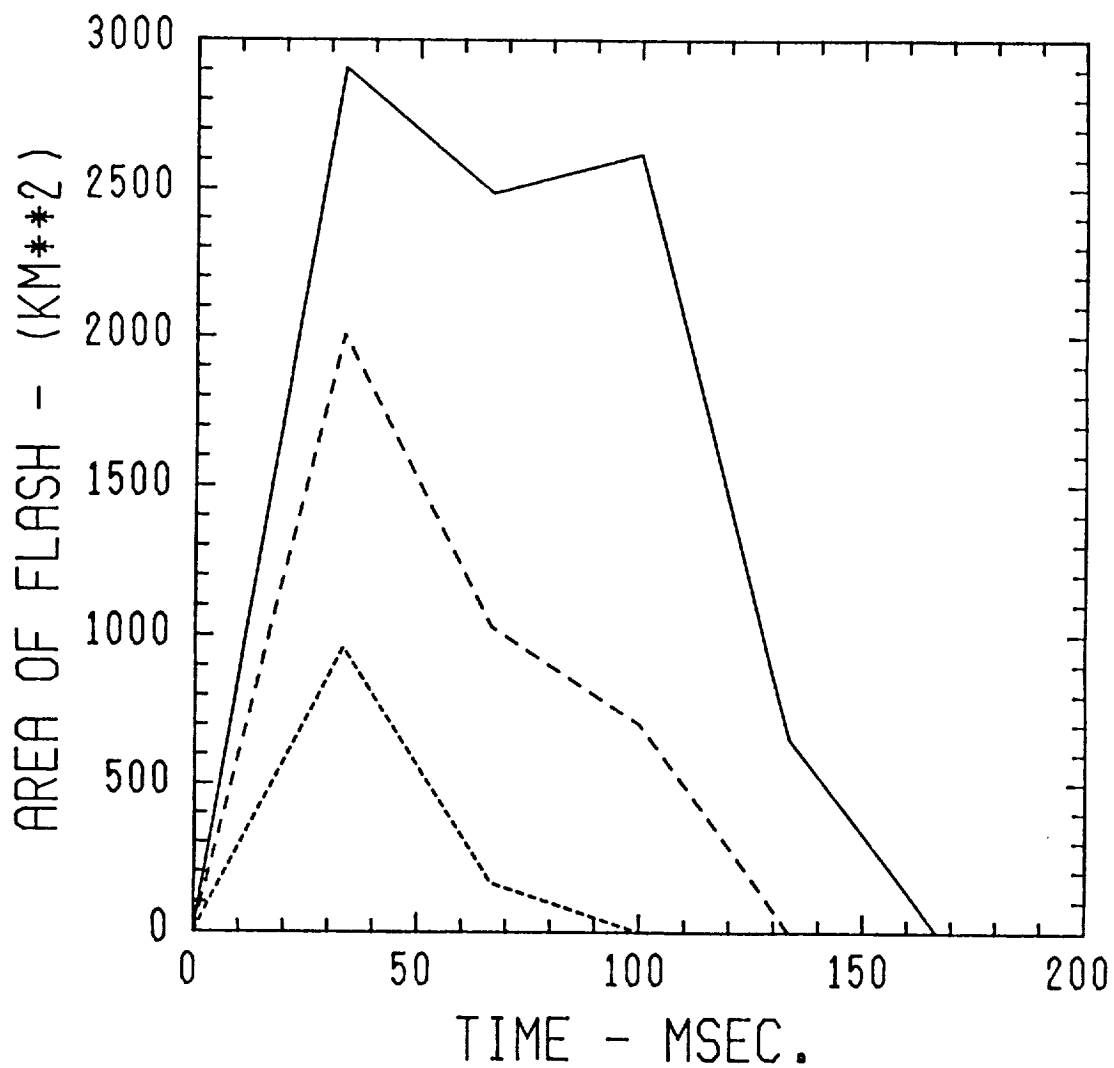


Figure 63: This figure shows the fluctuations in the area of a flash over its lifetime, for events 142 through 144 of STS-51J. These events were not simultaneous. These curves show some of the events of STS-51J which had a short duration. Notice that the time interval to the largest area is shorter than the remainder of the duration of these flashes. (Flash 142: solid curve; Flash 143: long dash curve; Flash 144: short dash curve).

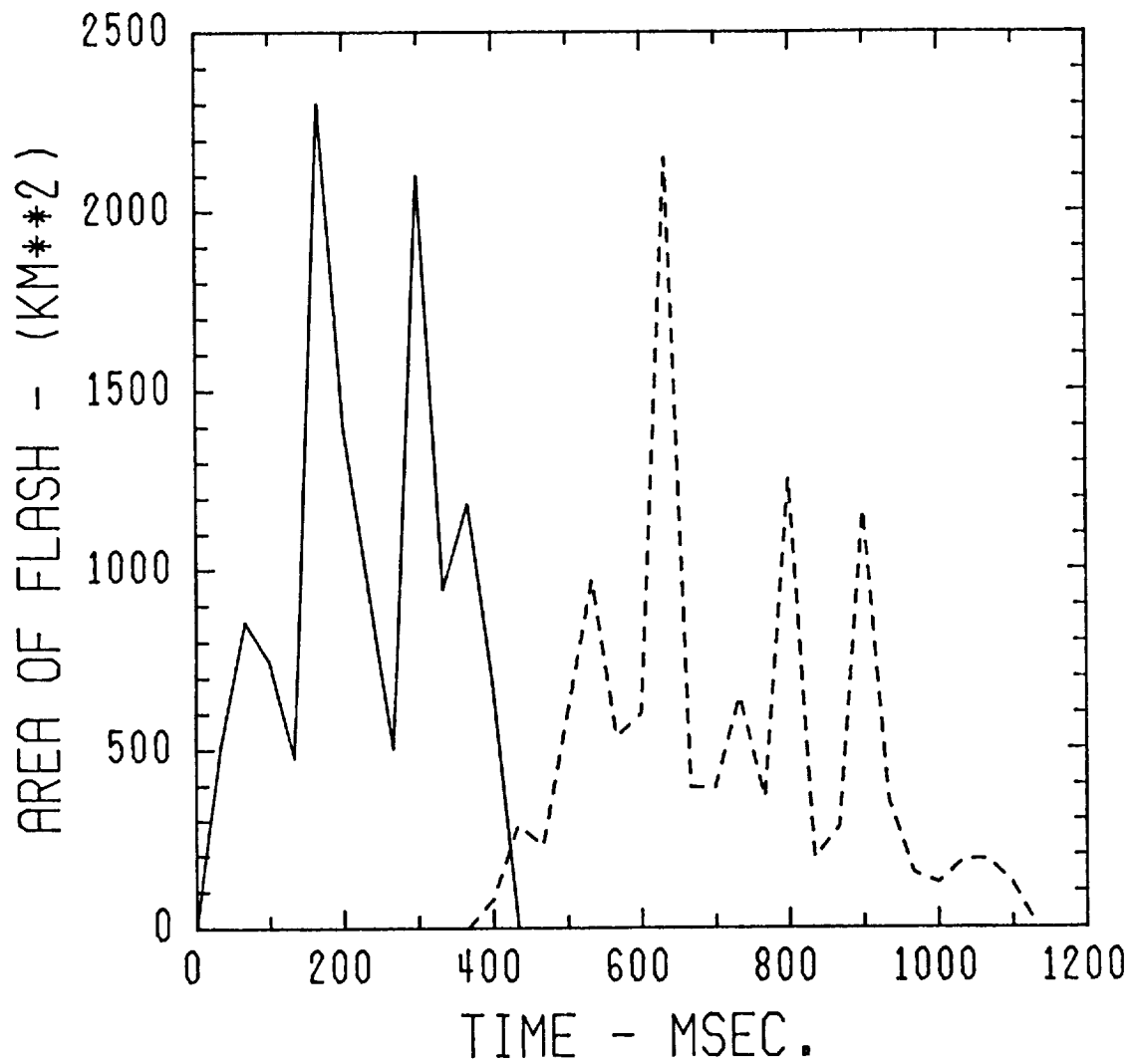


Figure 64: This figure shows the fluctuations in the area of a flash over its lifetime, for simultaneous events 43 and 44 of STS-51J. These two events were 130 km apart. Event 43 is typical of an average STS-51J flash in its size, duration, and number of peaks in the area curve. (Flash 43: solid curve; Flash 44: broken curve.)

The distances between flashes 6 and 7, and flashes 7 and 8 of STS-41D were 25 km and 5 km, respectively (Figure 65). Flashes 6 and 7 began at the same time, while flash 8 appeared at a later time. The lifetimes of flashes 7 and 8 fall within that of flash 6.

Figure 66 shows flashes 31 and 32 of STS-51J. These two flashes were separated by 50 km. In this case, the lifetime of the second flash overlaps approximately half the lifetime of the first flash. The distance between flashes 9 and 10 of STS-51J was 150 km (Figure 67). Flash 10 appeared near the last 300 ms of the lifetime of flash 9.

Flashes 59 through 65 of STS-51J are shown in Figure 68. In this case we have a series of seven overlapping flashes. Flash 59 appeared first, followed by flash 60, 100 ms later. Towards the end of the lifetime of flash 59, flash 61 and then flash 62 appeared. Flashes 60 and 62 continue on after flashes 59 and 61 had ended. Near the end of the lifetime of flash 60, and when half the duration of flash 62 had passed, flash 63 appeared. Flash 64 appeared 166 ms later, but was very short lived. Flash 65 then began 33 ms after the end of flash 62. The greatest number of flashes occurring at once was four, near 400 ms.

Flashes 25 through 30 of STS-9 are shown in Figure 69. From 133 ms to 233 ms there were six lightning events present at the same time. The area curve of flash 29 is difficult to see. It lies close to the time axis. Both Figures 68 and 69 show flashes which overlap at various points in their lifetime, and flashes whose entire duration falls within the lifetime of another flash.

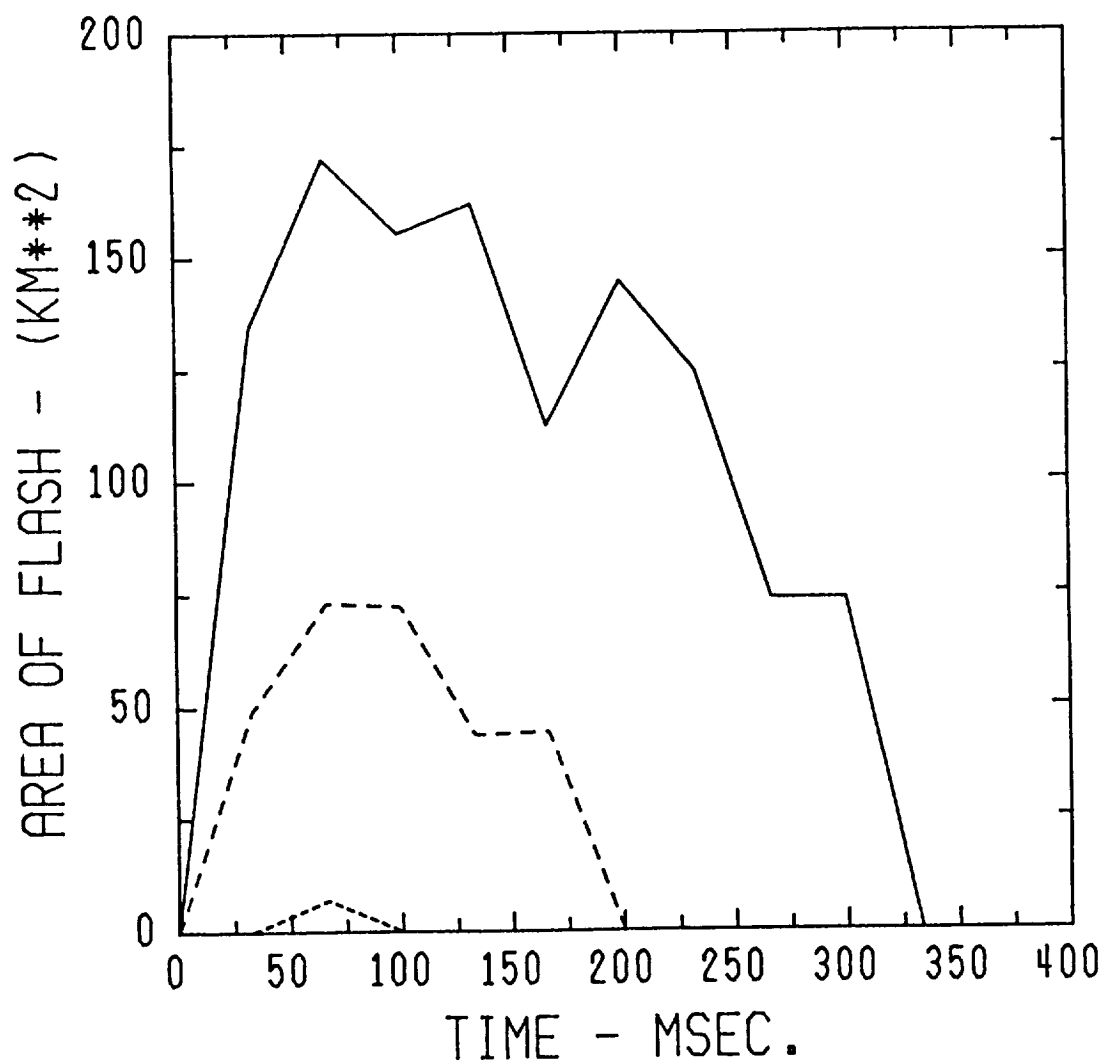


Figure 65: This figure shows the fluctuations in the area of a flash over its lifetime, for simultaneous events 6 through 8 of STS-41D. The distance between events 6/7 was 25 km, while that between events 7/8 was 5 km. The lifetimes of events 7 and 8 occurred within the lifetime of event 6. (Flash 6: solid curve; Flash 7: long dash curve; Flash 8: short dash curve).

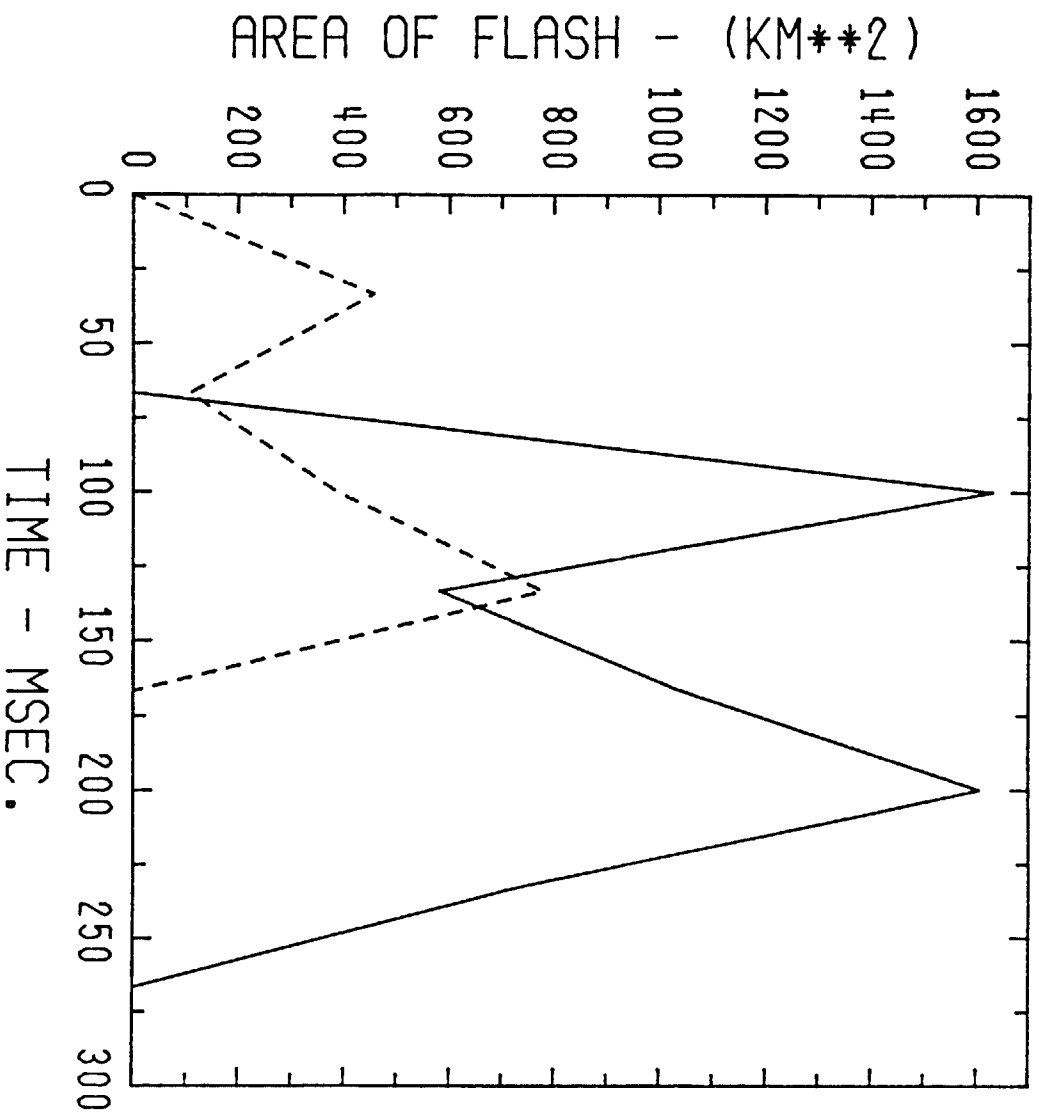


Figure 66: This figure shows the fluctuations in the area of a flash over its lifetime, for simultaneous events 31 and 32 of STS-51J. These two events were 50 km apart. (Flash 31: broken curve; Flash 32: solid curve).

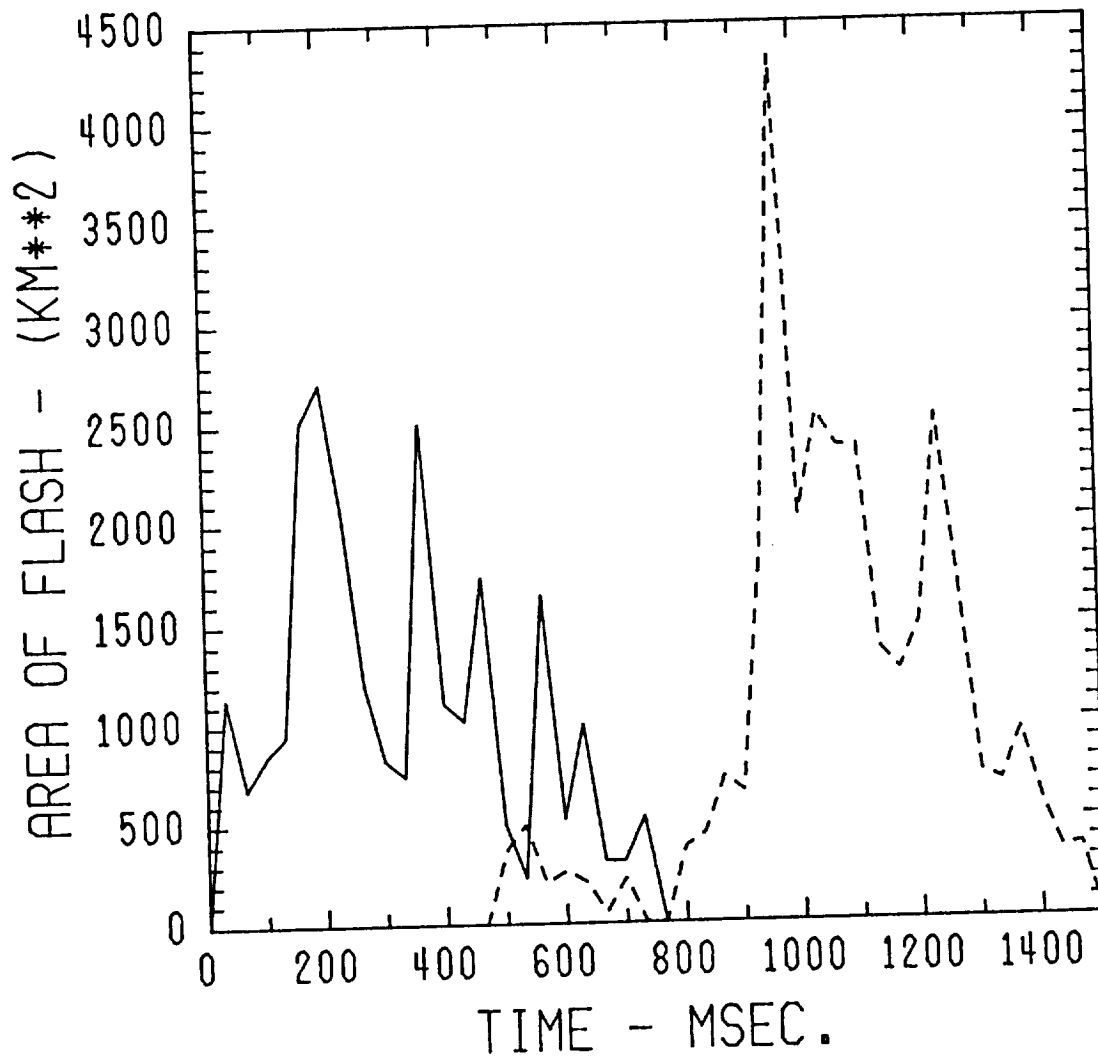


Figure 67: This figure shows the fluctuations in the area of a flash over its lifetime, for simultaneous events 9 and 10 of STS-51J. These two events were 150 km apart. (Flash 9: solid curve; Flash 10: broken curve).

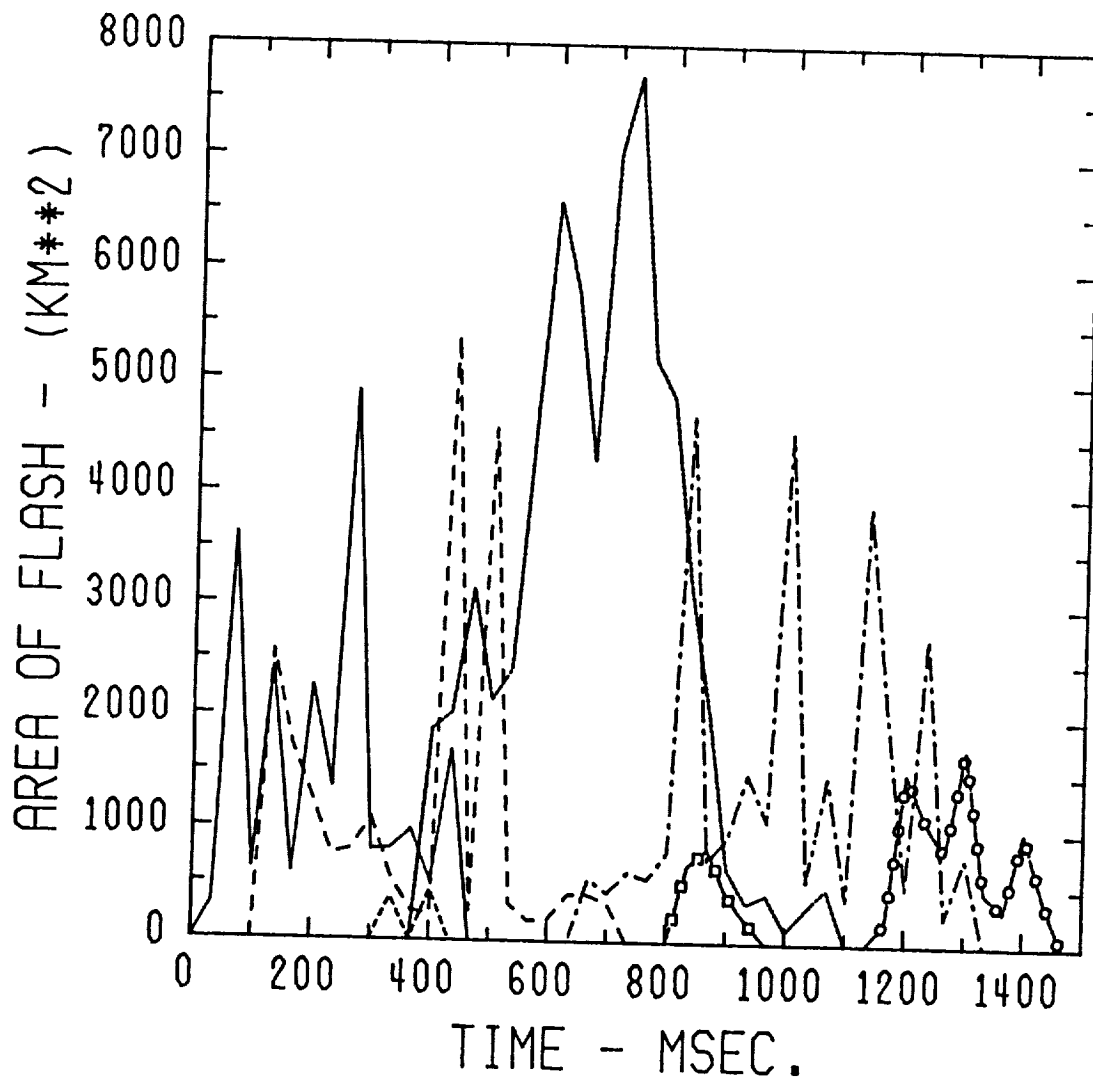


Figure 68: This figure shows the fluctuations in the area of a flash over its lifetime, for simultaneous events 59 through 65 of STS-51J. Near 400 ms, four of these events were active at the same time. The distance between events 59/60, 59/61, and 61/62 was 10 km, 5 km, and 115 km, respectively. The distance between events 60/63, 64/62, and 63/65 was 60 km, 20 km, and 20 km, respectively. (Flash 59: solid curve; Flash 60: long dash curve; Flash 61: short dash curve; Flash 62: dotted curve; Flash 63: dash-dot curve; Flash 64: dash-square curve; Flash 65: dash-circle curve).

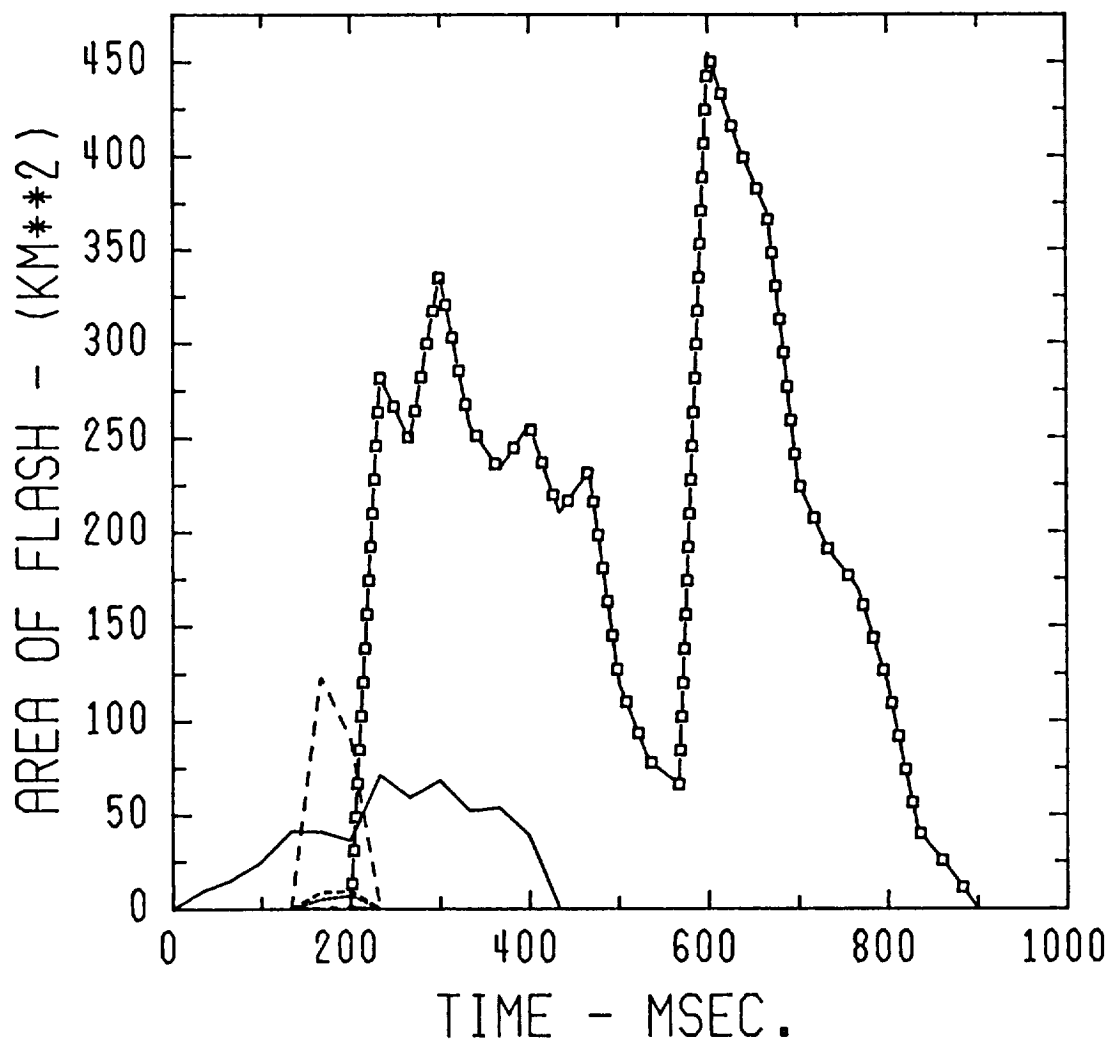


Figure 69: This figure shows the fluctuations in the area of a flash over its lifetime, for simultaneous events 25 through 30 of STS-9. The curve for event 29 lies near the lower axis. At 133 ms, six events were active at the same time. The distance between events 25/26, 26/27, 27/28, 26/29, and 25/30 was 10 km, 10 km, 15 km, 15 km, and 30 km, respectively. (Flash 25: solid curve; Flash 26: long dash curve; Flash 27: short dash curve; Flash 28: dotted curve; Flash 29: dash-dot curve; Flash 30: dash-square curve).

Flashes 38 and 39 of STS-9 were 10 km apart (Figure 70). Both of these flashes began at the same time. The persistent bright spot mentioned earlier appeared in both of these events.

An interesting and unique set of simultaneous flashes is shown in Figure 71. Flashes 66 through 68 of STS-9 all have a very similarly shaped area curve over the duration of the flash. All three flashes began and ended at the same time. Flashes 66 and 67 were 5 km apart, and flashes 67 and 68 were 3 km apart. More will be said about these three events in the discussion section.

e) The shape of the area curves.

The curves of the variation in the area of the illumination over time appear to fall into one of five categories, based on the shape of the curve. The categories are: 1. Bimodal curves which have two major peaks; 2. Curves in which the maximum area is reached near the beginning of the lifetime of the flash; 3. Curves in which the maximum area is reached near the end of the lifetime of the flash; 4. Curves whose maximum area is reached near one-half the total duration of the flash; and 5. Curves which can be described by either a combination of the above categories, or that are totally different from any of the above categories. Figures 72 through 83, along with some of the previous plots of area versus time, illustrate these five shape categories.

The area curves, termed bimodal consist of two major peaks in the area which are separated by at least 100 ms or more. There may be other peaks in this curve, but they are not as distinct as the two major peaks. This category has three subclasses. The first

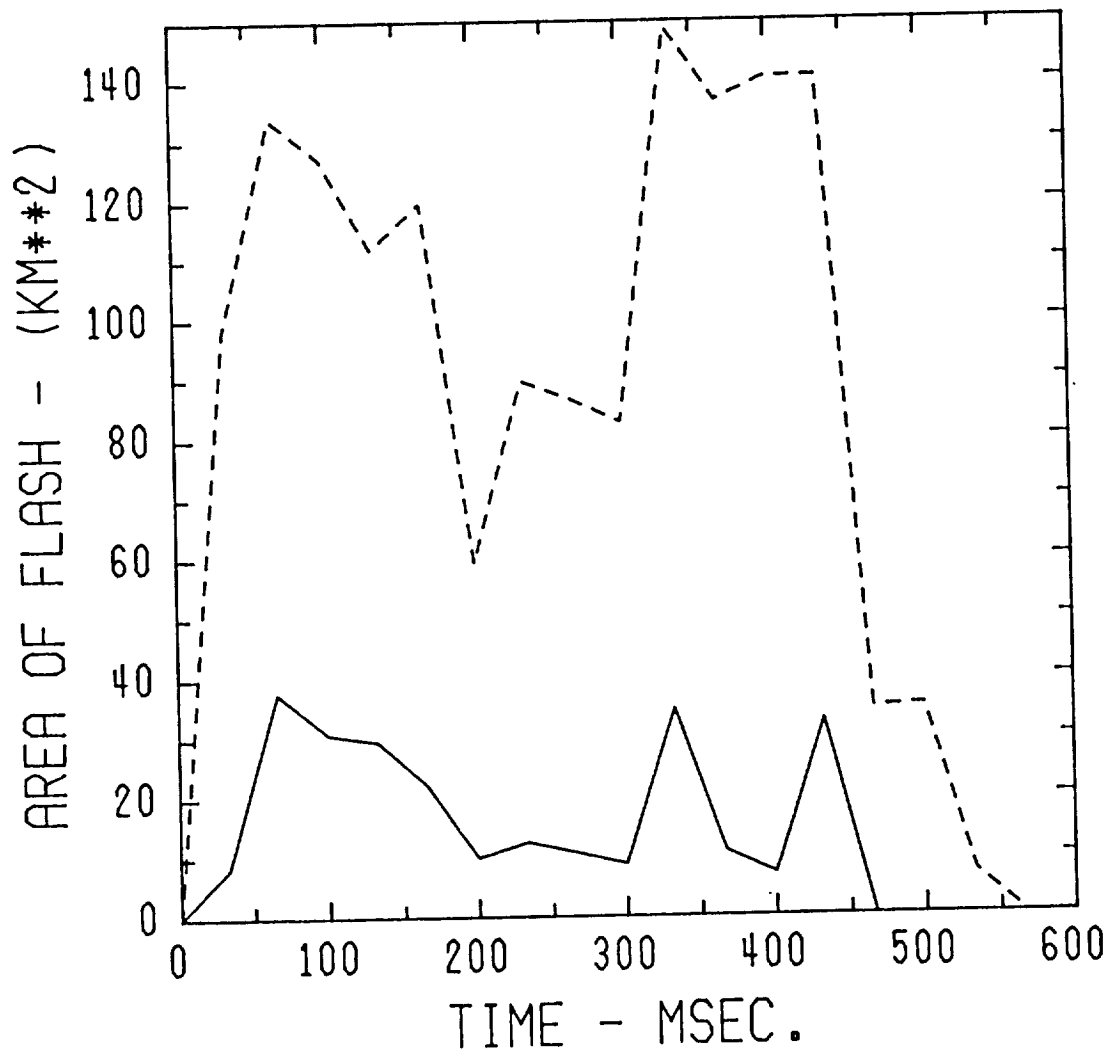


Figure 70: This figure shows the fluctuations in the area of a flash over its lifetime, for simultaneous events 38 and 39 of STS-9. These two events were 10 km apart. Both had a bright spot. (Flash 38: solid curve; Flash 39: broken curve).

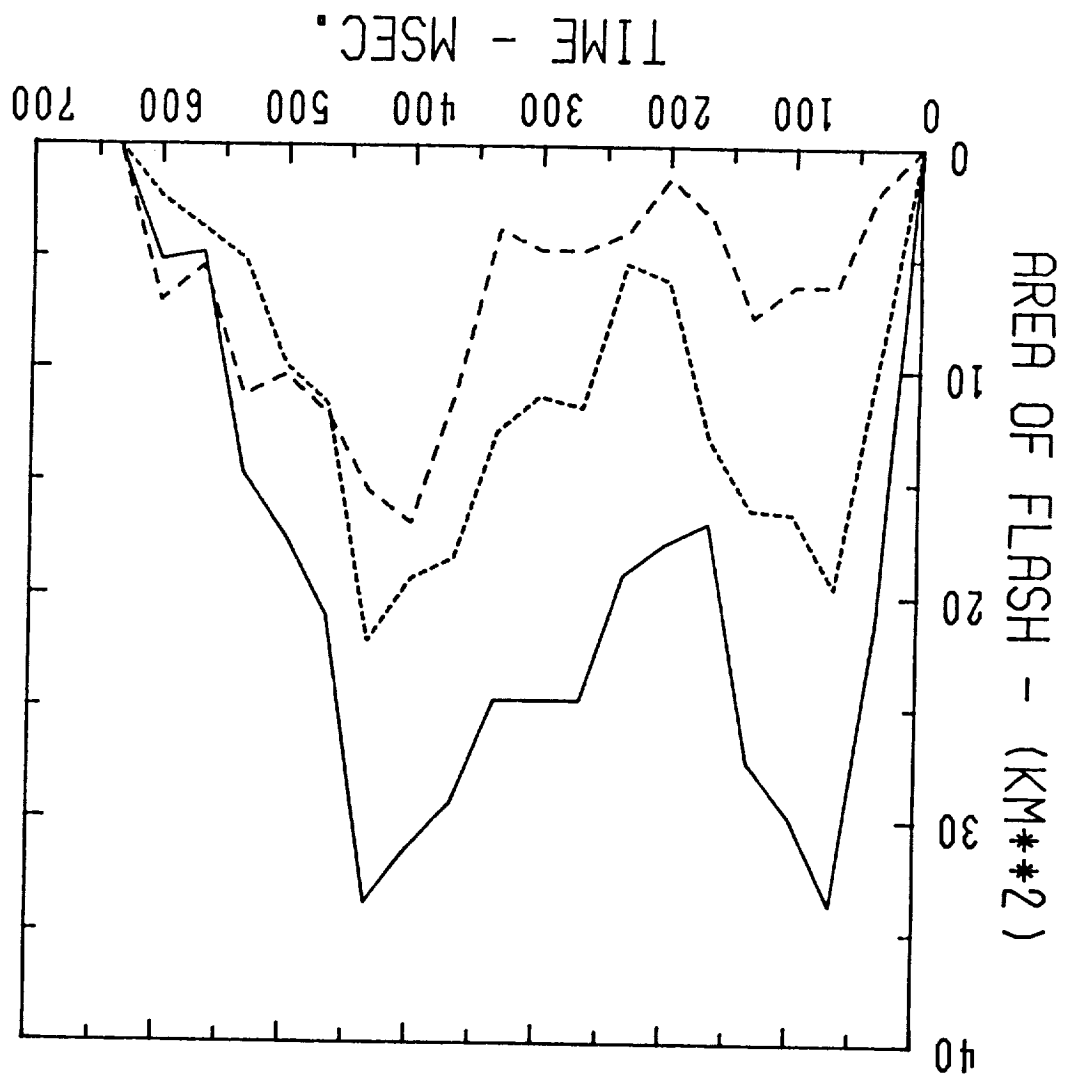


Figure 71: This figure shows the fluctuations in the area of a flash over its lifetime, for simultaneous events 66 through 68 of STS-9. Events 66/67, and 67/68 were separated by 5 km and 4 km, respectively. (Flash 66: solid curve; Flash 67: long dash curve; Flash 68: short dash curve).

subclass is called the "horn" curve because the major peaks in the area are sharp, and occur at the beginning and end of the lifetime of the flash. The first large peak in the area is not preceded by any other peaks and the second large peak in the area is not followed by any other peaks (Figure 72). The area curve of flash 151 of STS-51J is another example of the horn curve (Figure 73). The area curve of flash 152 falls into the category of curves whose maximum area occurs at or near the end of the flashes lifetime. A second subclass of the bimodal curve is the "mirror image" curve. The two major peaks in the area of this type of bimodal curve are broader than those of the horn curve, and may have small fluctuations within the peak itself. The fluctuations in the area of the first major peak mirror those of the second major peak, though they are not necessarily of the same magnitude. The area curve of flash 45 of STS-9 is an example of the mirror image bimodal curve (Figure 74). Other examples of this type of curve can be found in Figures 55 (flash 3) and 71. The third subclass of the bimodal type curves is the 'repeated image' curve. The repeated image bimodal curve is similar to the mirror image curve in that it has two major peaks in the area that are broad, with fluctuations within the peaks. However, in this subclass, the pattern of the fluctuations in the area within the peaks is repeated, instead of being reversed. The curve of flash 39 of STS-9 (Figure 70) is one example of this type of curve. 14.8% of the curves of the area of the illumination versus time could be classified as bimodal curves.

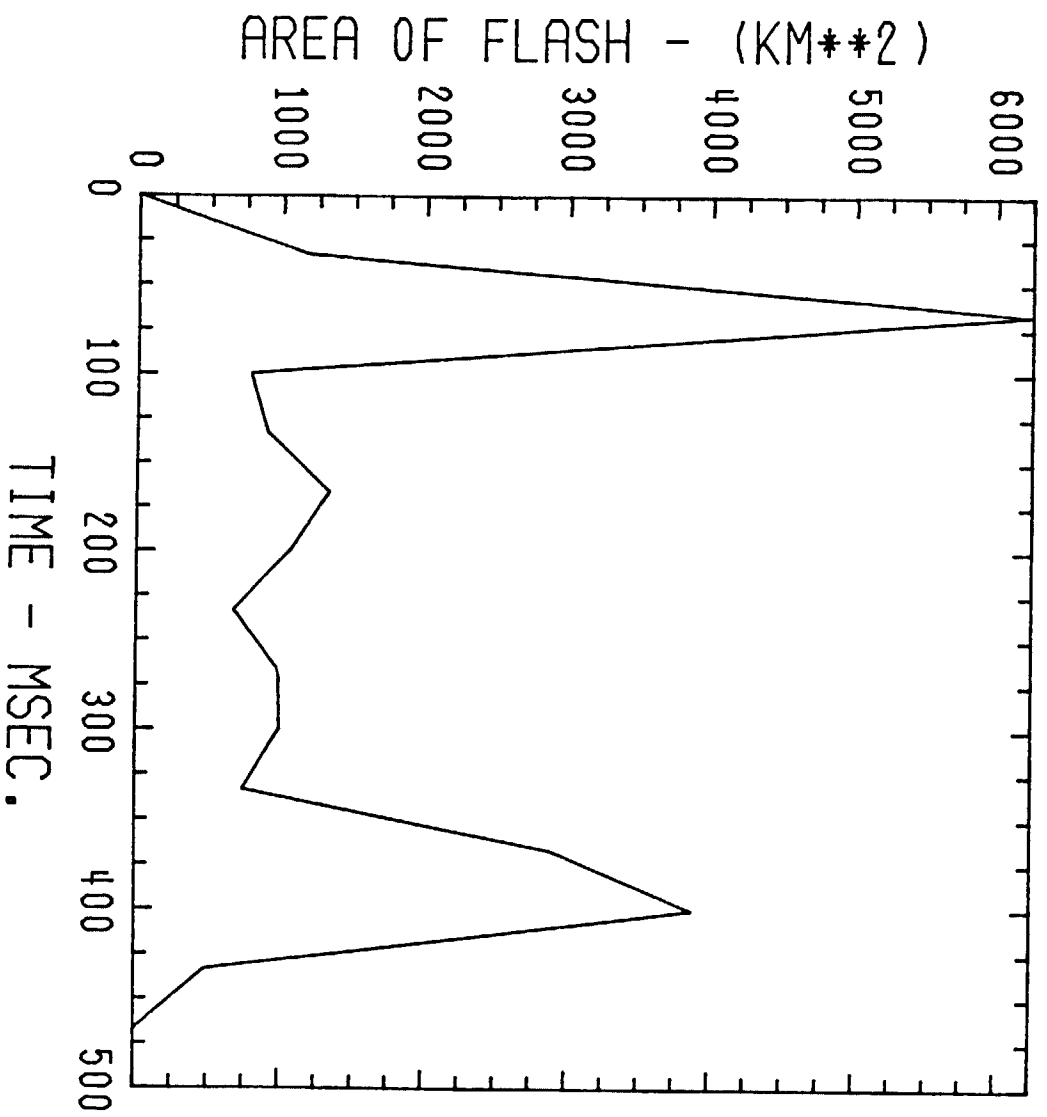


Figure 72: This figure shows the fluctuations in the area of a flash over its lifetime, for event 5 of STS-51J. The curve of this event illustrates the 'horn' shaped curve.

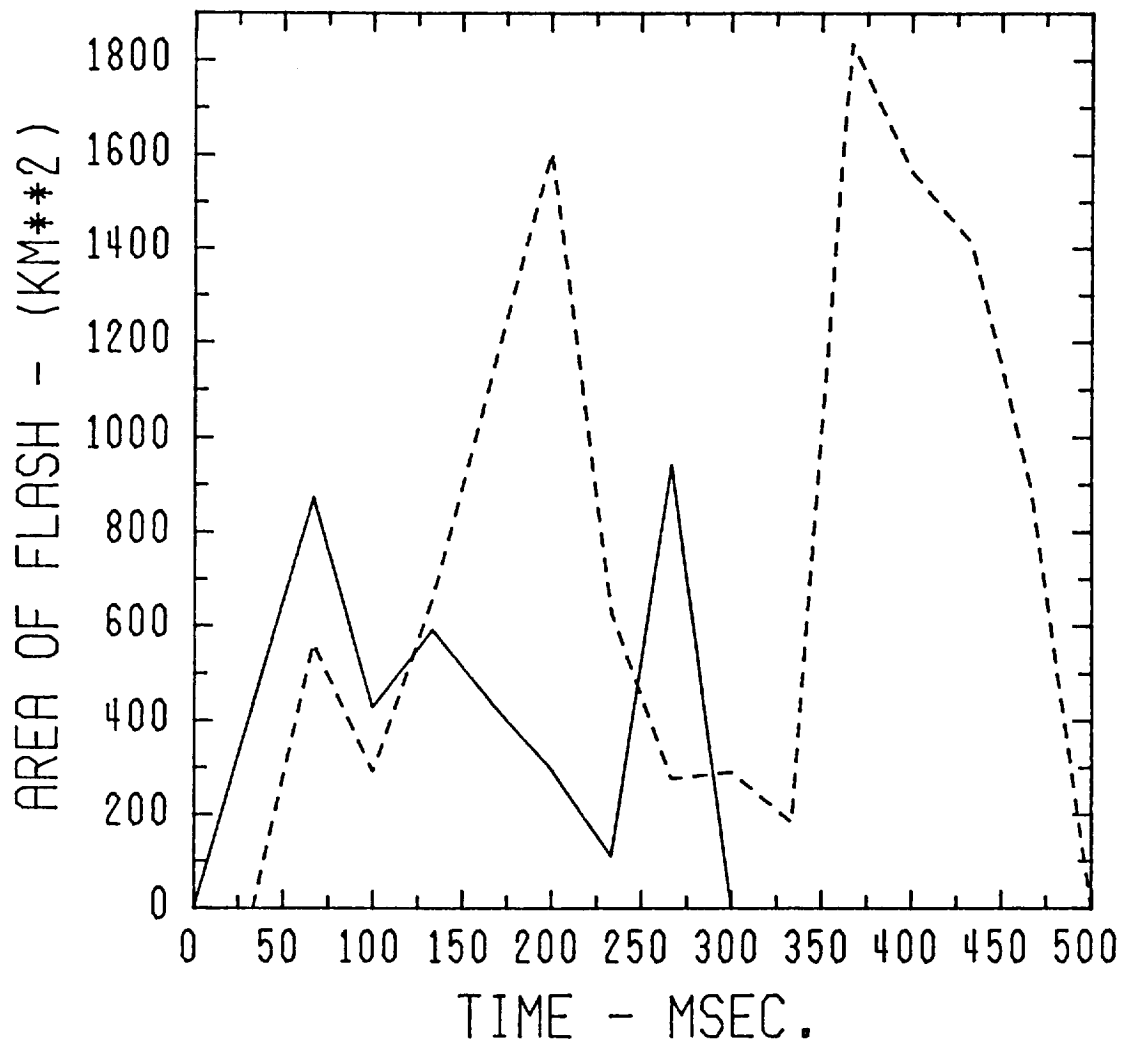


Figure 73: This figure shows the fluctuations in the area of a flash over its lifetime, for simultaneous events 151 and 152 of STS-51J. These two events were 150 km apart. Flash 151 has a 'horn' type curve, while the curve of flash 152 was classified as a maximum area near the end of the lifetime curve. (Flash 151: solid curve; Flash 152: broken curve).

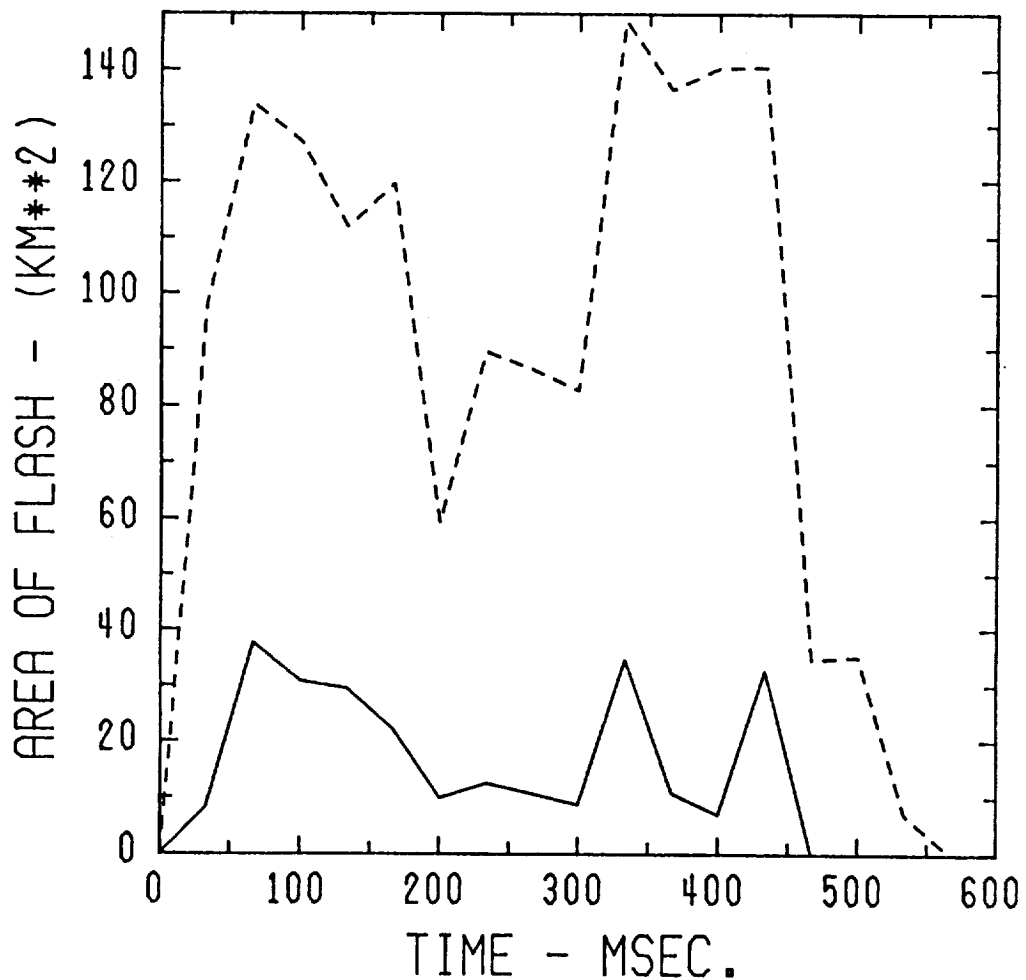


Figure 74: This figure shows the fluctuations in the area of a flash over its lifetime, for simultaneous events 44 through 46 of STS-9. Flashes 44/45, and 44/46 were separated by 8 km, and 9 km, respectively. Curve 45 is an example of a 'mirror image' curve, curve 46 is an example of a maximum peak in the middle curve, and curve 44 is an example of a curve which does not fit into any of the specified shape categories. (Flash 44: solid curve; Flash 45: long dash curve; Flash 46: short dash curve).

The area curves of events, in which the maximum area was attained near the beginning of the lifetime of the flash, and was then followed by peaks in the area curve which became successively smaller with time, were classified under the second category. These curves were broken down into two subclasses: those which reached their maximum peak when they first appeared, and those whose maximum area occurred near the beginning of the flash, but was preceded by several small peaks or fluctuations in the area. The area curve of flash 98 of STS-51J is one example of a curve of the first subclass (Figure 75). Notice that as time increases, each successive fluctuation in the area decreases. Other examples of this type of curve may be found in Figures 50 (flash 2), 56 (flash 7), and 63. The curves of flashes 100 and 37 of STS-51J (Figures 75 and 76, respectively), are examples of the second subclass mentioned above. Again, as time increases, the peaks in the area, following the maximum area, get successively smaller. This type of curve can also be found in Figures 50 (flashes 1,3,4, and 5), 55 (flash 2), 65 (flashes 6 and 7) and 67 (flash 9). The area curve of flash 63 of STS-51J shows an interesting variation of this type of curve shape (Figure 68). Approximately 23% of the area curves could be classified as reaching their maximum area at or near the beginning of the flash.

The third classification of the area curves includes those flashes which reach their maximum area near the end of their duration. This group can also be divided into two subclasses. The first subclass is made up of the area curves from lightning events

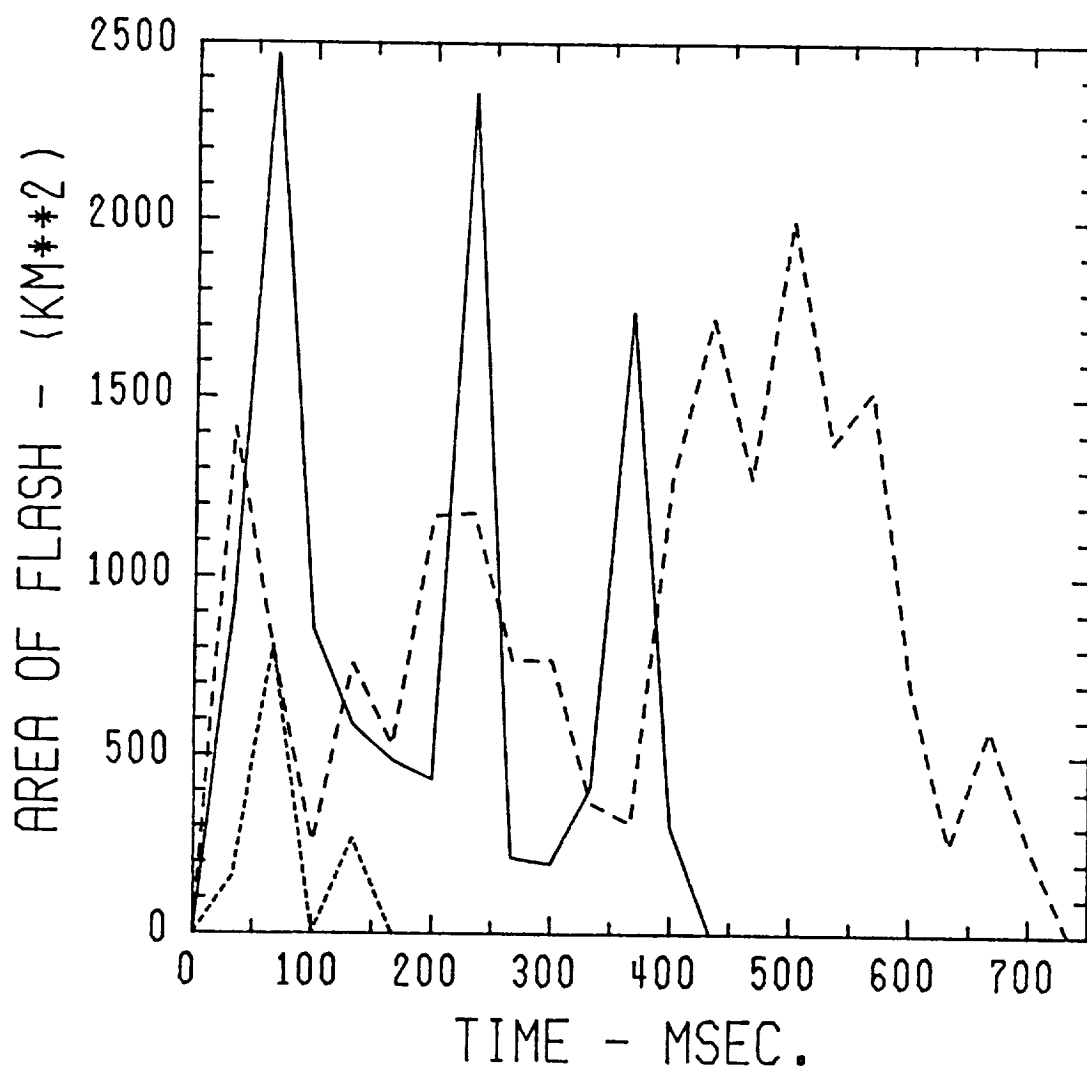


Figure 75: This figure shows the fluctuations in the area of a flash over its lifetime, for events 98 through 100 of STS-51J. These events were not simultaneous. The curves for events 98 and 100 are examples of the maximum peak at the beginning of the lifetime category. Note how each successive peak of these two curves gets smaller. (Flash 98: solid curve; Flash 99: long dash curve; Flash 100: short dash curve).

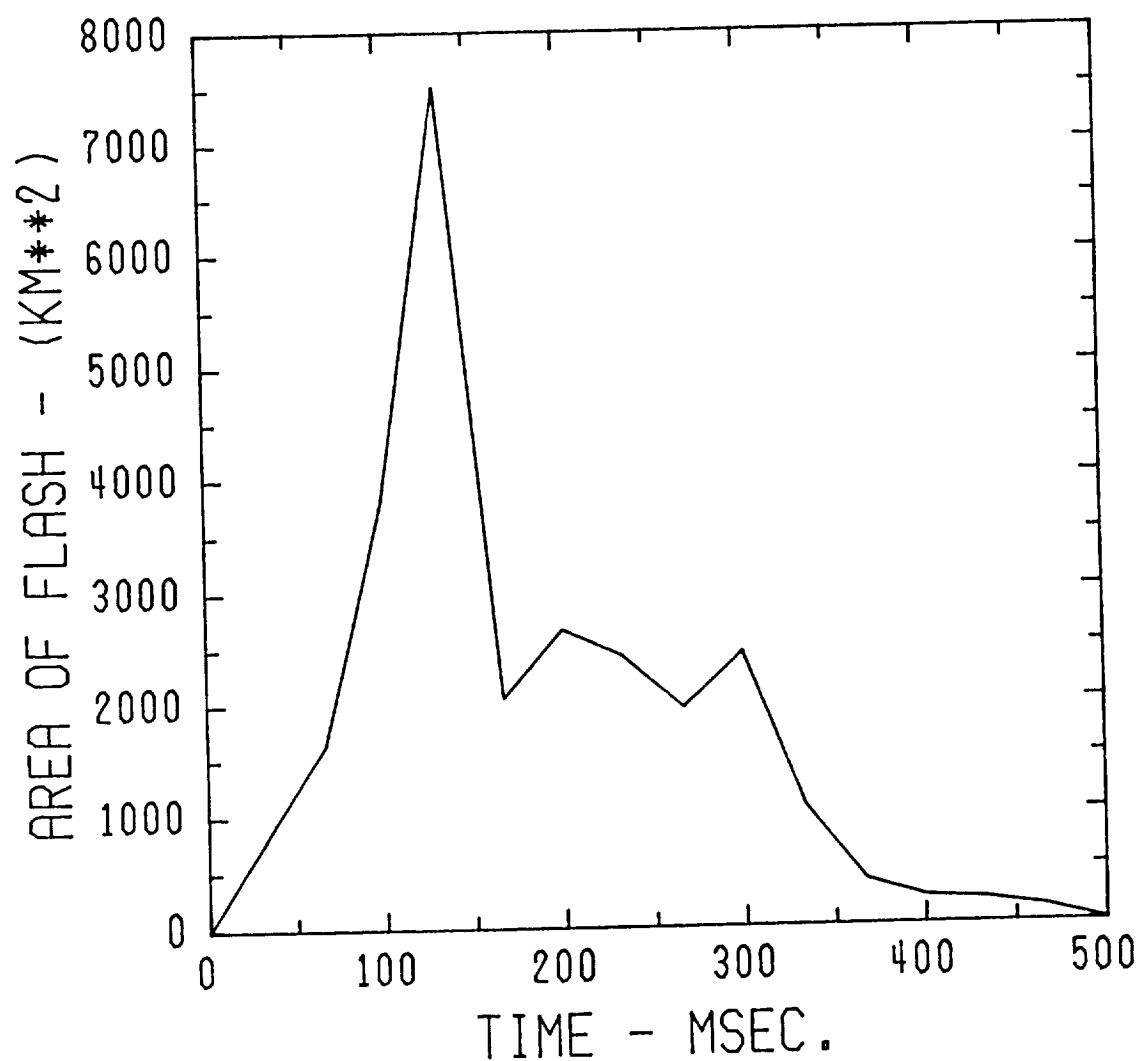


Figure 76: This figure shows the fluctuations in the area of a flash over its lifetime, for event 37 of STS-51J. This curve is an example of the maximum peak near the beginning of the lifetime shape category.

that attained their maximum area on the last video frame in which they appeared. The second subclass consists of curves in which the maximum area occurs near the end of the lifetime of the flash, and is followed by small fluctuations or peaks in the area curve. In both of these subclasses, the maximum area is preceded by a series of peaks in the area which get increasingly larger over the lifetime of the flash. The area curves of flashes 131 and 133 are examples of the second and the first subclasses respectively (Figure 77). The increasing trend of the peaks in the area over time is clearly seen in the curve for flash 133. Flash 132 falls into the bimodal category. The area curves of flashes 1 and 2 of STS-51Jz (those events which were photographed with a zoom lens on STS-51J), also illustrate the successive increase in the peaks in the area curves (Figure 78). Flash 3 was classified as a maximum area at one-half the duration curve. Events 179 and 180 of STS-51J occurred simultaneously (Figure 79). The curve of flash 179 fits into the maximum area near the end of the duration category, while the area curve of flash 180 is classified as having the maximum area occurring near one-half the duration of the flash. Approximately 28% of all the area curves were classified as having their maximum area occur near the end of the duration of the flash.

The area curves of flashes 14 and 15 of STS-51J are examples of the two subclasses of the category of curves in which the maximum area occurs at or near half the duration of the flash (Figure 80). The area curve of flash 14 is a member of the subclass in which the maximum peak is surrounded by other peaks of varying

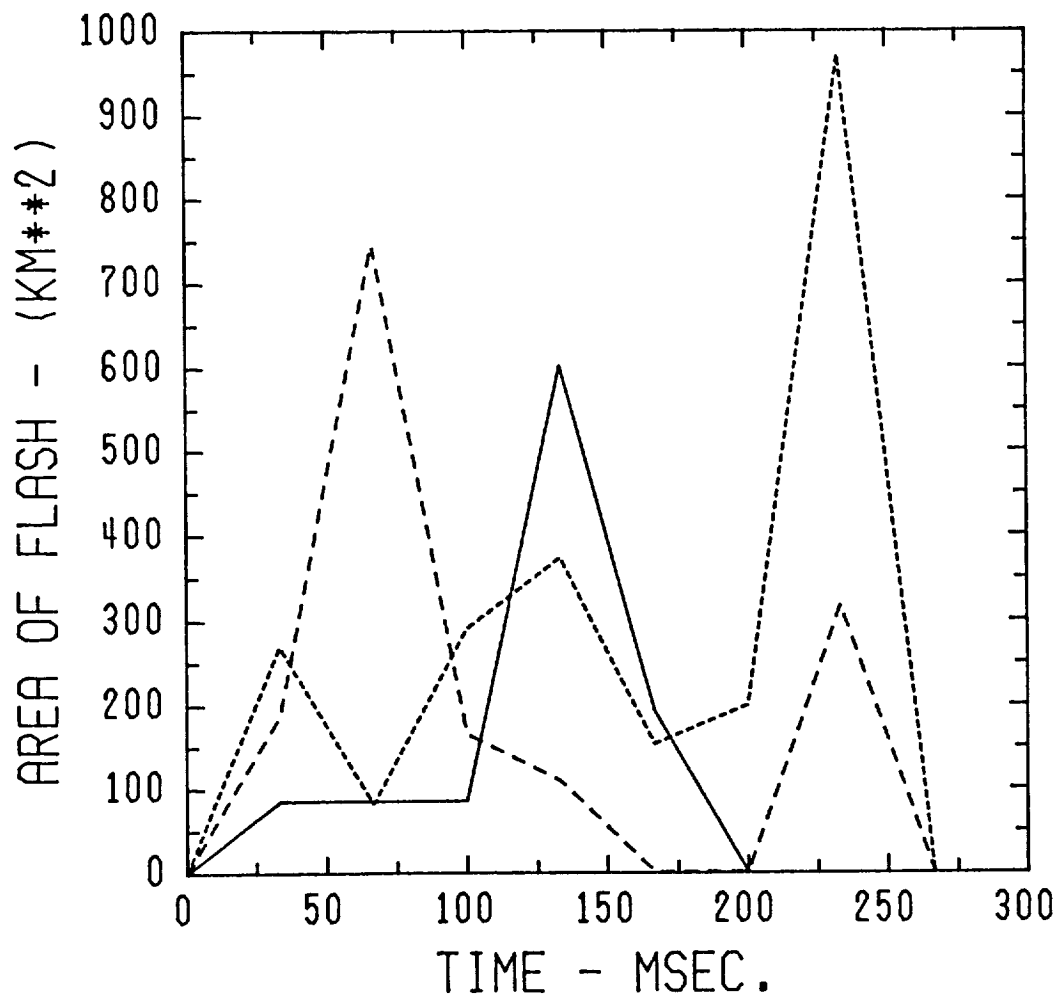


Figure 77: This figure shows the fluctuations in the area of a flash over its lifetime, for events 131 through 133 of STS-51J. These events were not simultaneous. Flashes 131 and 133 have curves which fall into the maximum area at or near the end of the duration category, while the curve of flash 132 was classified as bimodal. (Flash 131: solid curve; Flash 132: long dash curve; Flash 133: short dash curve).

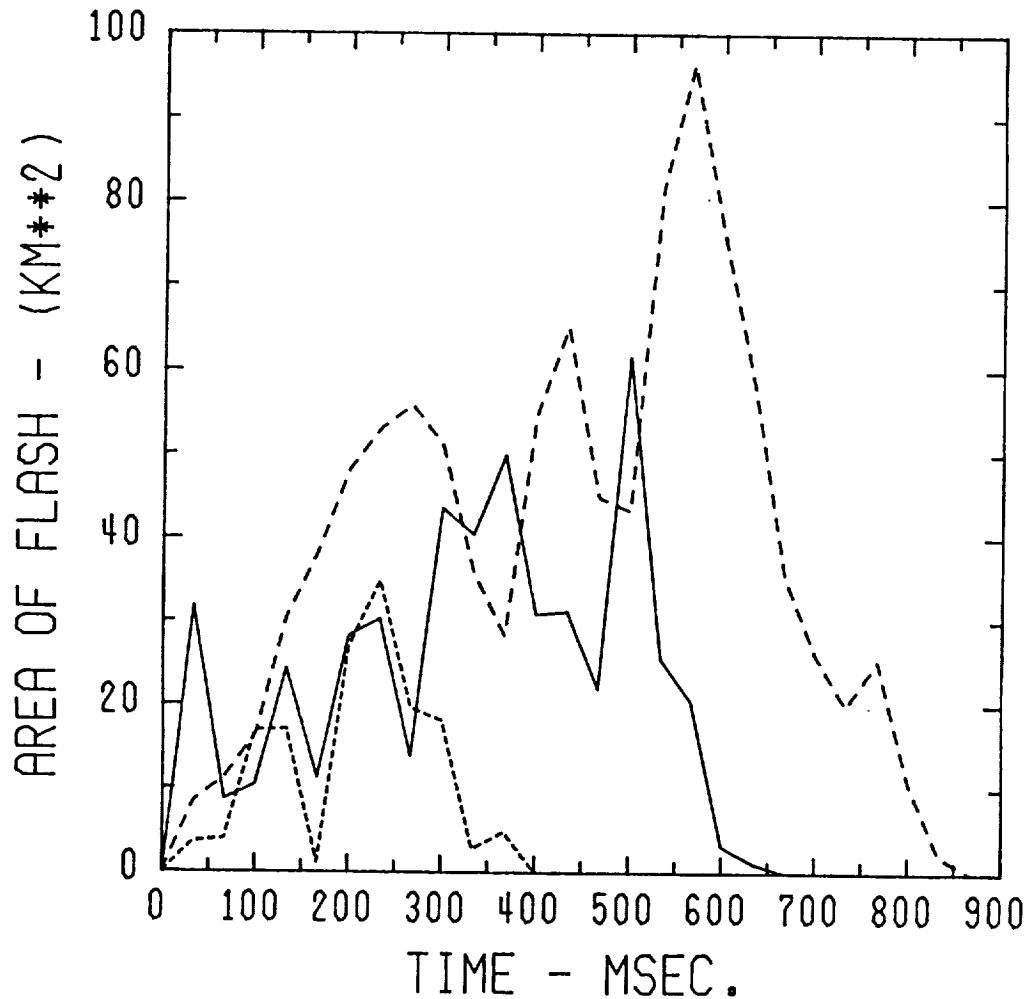


Figure 78: This figure shows the fluctuations in the area of a flash over its lifetime, for events 1 through 3 of STS-51Jz, (the events of STS 51J which were photographed with the zoom lens). They did not occur simultaneously. The curves illustrate the trend of successively larger peaks in the area curve over time. (Flash 1: solid curve; Flash 2: long dash curve; Flash 3: short dash curve).

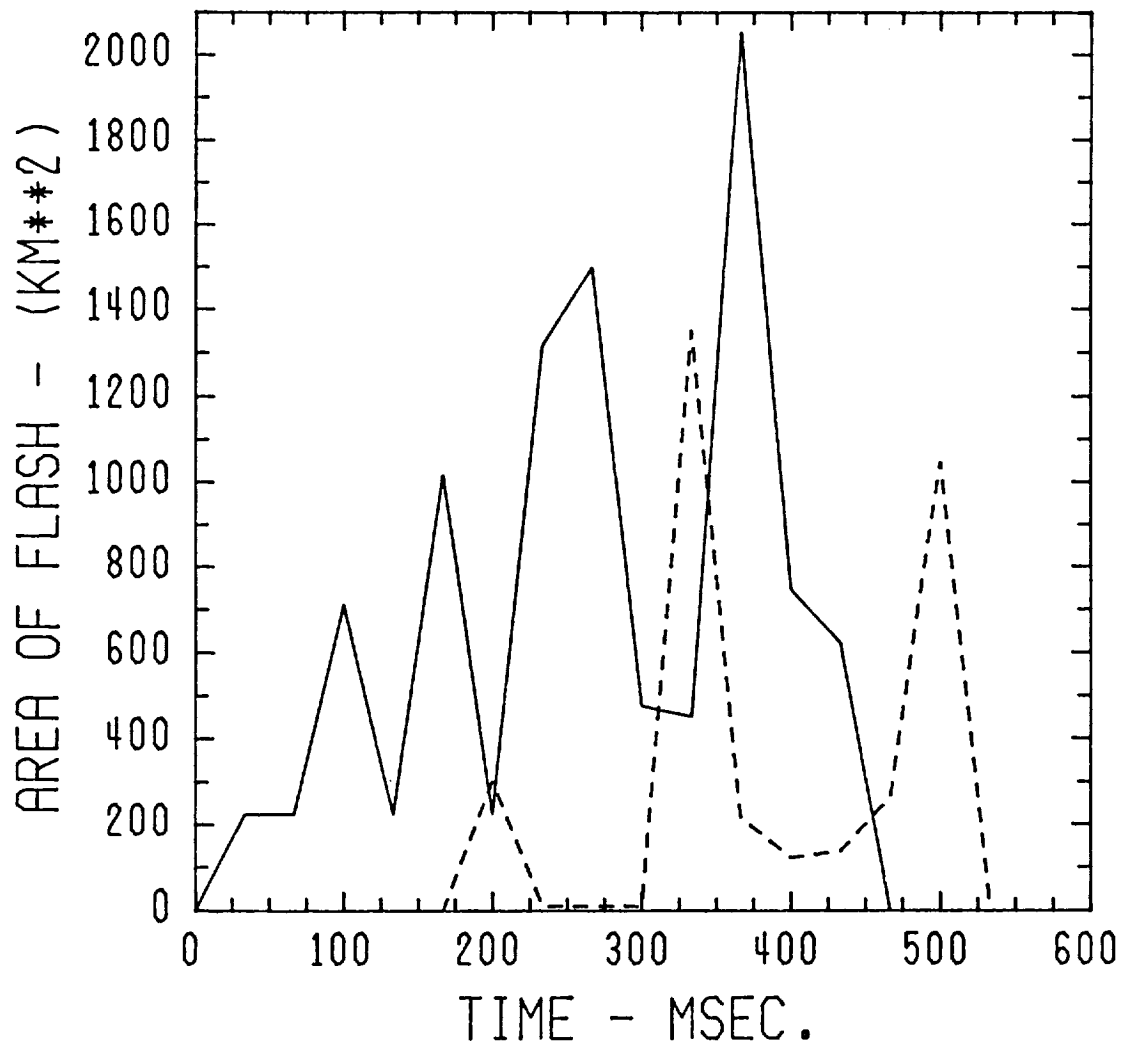


Figure 79: This figure shows the fluctuations in the area of a flash over its lifetime, for simultaneous events 179 and 180 of STS-51J. Curve 179 is an example of a maximum peak near the end of the flash duration type curve, while the area curve of event 180 is an example of a maximum peak in the middle curve. These two events were 30 km apart. (Flash 179: solid curve; Flash 180: broken curve).

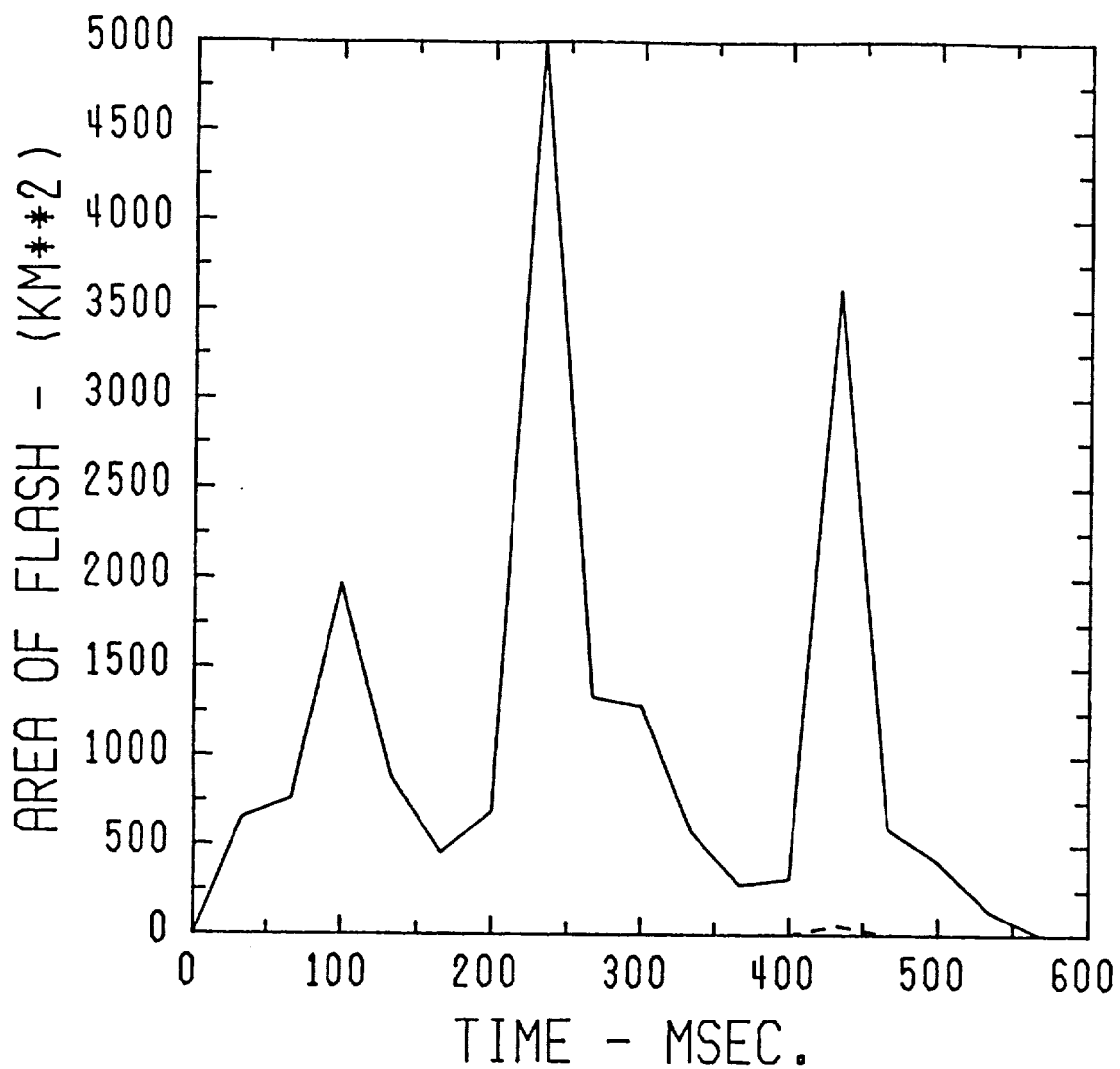


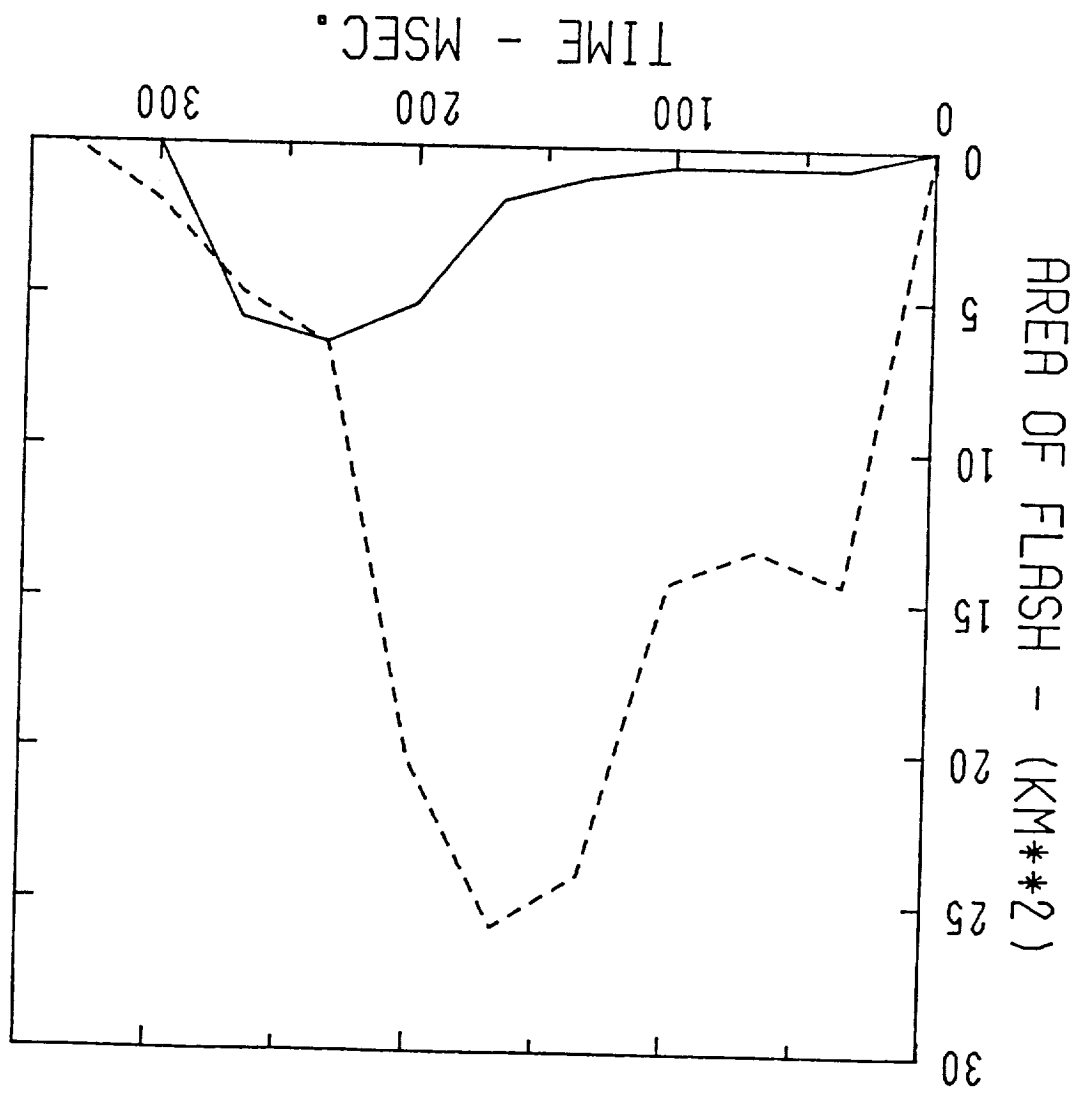
Figure 80: This figure shows the fluctuations in the area of a flash over its lifetime, for simultaneous events 14 and 15 of STS-51J. These two events were 40 km apart. Both curves fall into the maximum area near the middle shape category. (Flash 14: solid curve; Flash 15: broken curve).

size. In some cases the peaks get increasingly larger preceding the maximum peak, and then successively smaller after it. The area curve of flash 15 is a member of the subclass whose maximum peak is also its only peak, and occurs at or near the middle of the lifetime of the flash. Approximately 24% of the area curves fit into the maximum area at one-half the duration category. Flash 94 is another example of an event whose maximum area occurred near the middle of its lifetime, while flash 93 is an event whose maximum area occurred near the end of its lifetime (Figure 81). Other examples of this type of area curve can be found in Figures 51, 54 (flash 134), 57, 58 (flashes 17 and 20), and 68 (flashes 60, 62, 64, and 65).

Approximately 90% of the curves of the area were classified into one of the preceding four categories. About two-thirds of these area curves strongly exhibited the traits of one of the four groups. The other one-third varied somewhat from the characteristics of a given category, but still had the same basic shape, and time of the occurrence of the largest area of the flash with respect to the total duration of the flash, found in a given curve class.

The other 10% of the curves could not be put into one of the four categories either because they had characteristics which overlapped several categories, or because the curve was totally unique and could not be described by any of the above classifications. For example, the area curve of flash 53 of STS-51J generally shows a trend of successively increasing peaks preceding the maximum area, thereby possibly classifying it under the third category (Figure 82). However, there are two peaks, one at 366 ms

Figure 81: This figure shows the fluctuations in the area of a flash over its lifetime, for events 93 and 94 of STS-9. These two events did not occur simultaneously. Curve 93 is an example of the maximum area at the end type curve, while curve 94 is an example of the maximum area near the middle type curve. (Flash 93: solid line; Flash 94: broken curve).



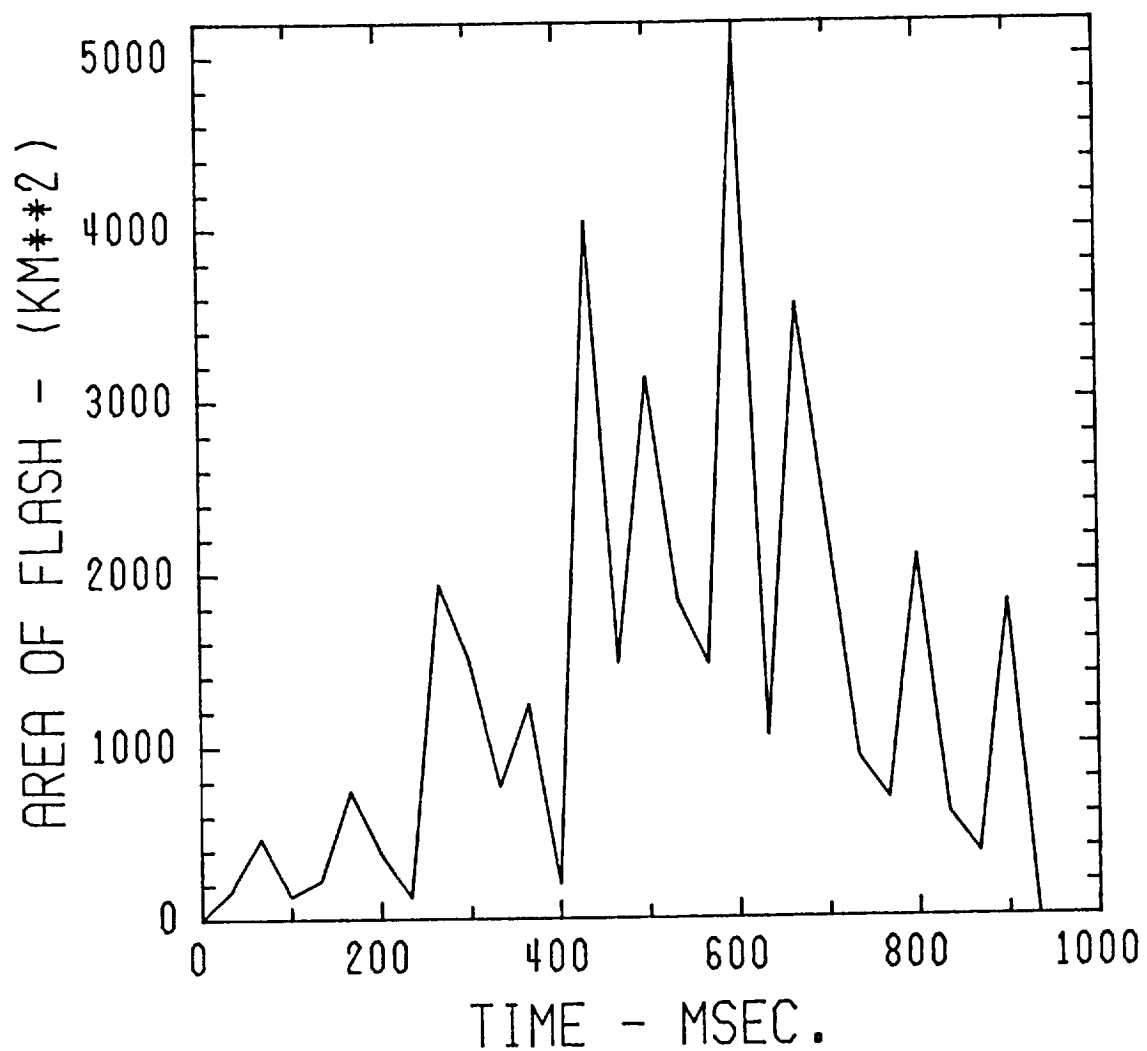


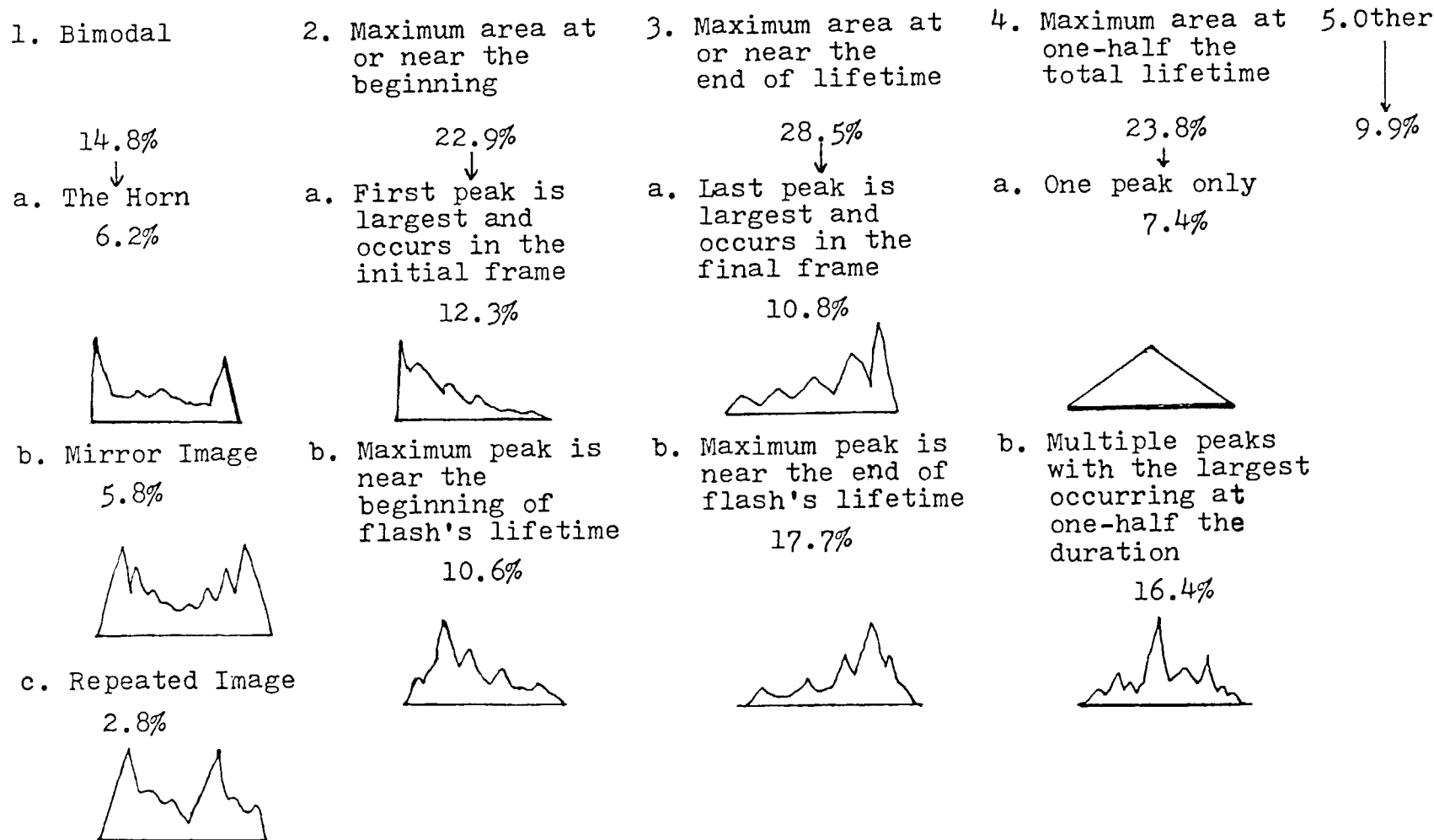
Figure 82: This figure shows the fluctuations in the area of a flash over its lifetime, for flash 53 of STS-51J. This curve does not fit into any of the first four shape categories given in the text.

and the other at 500 ms, which are smaller than the peaks which occur immediately before. The curve of flash 53 also doesn't quite fit into the maximum area in the middle of the duration of the flash category because the largest peak occurs at 65% of the total duration of this flash, and the curves in this category reached their maximum extent from 45% and 55% of their total duration. The curve of flash 38 of STS-9 (Figure 70) is another example of a curve which does not fit into any one shape category. This curve seems to be a combination of a maximum peak near the beginning of a flash curve, and a bimodal curve. The area curves of flash 84 of STS-51J (Figure 53), and flash 30 of STS-9 (Figure 69) are two more examples of curves which do not fit into one of the first four categories.

When considering the area curves of all flashes, none of the five shape categories was strongly favored. Figure 83 is a schematic diagram of the five shape categories of the area curves and their subclasses. The percentage of all 323 curves which fit into each group is indicated. The smallest percent of events fell into the 'other' category.

The percent of curves falling into a given shape category was also investigated for each flight. 31% of the flashes of STS-8 fit into both the maximum area near the beginning and maximum area near the middle of the duration categories. 88% of the STS-41D flashes fit into the maximum area near the beginning of the lifetime of the flash category. 40% of the STS-9 flashes fit into the maximum peak near the end of the lifetime of the flash category,

Figure 83: The percentage of the 323 area curves which fall into a given shape category. Each major category, denoted by a number, is further divided into its subclasses.



followed by 21% in both the maximum area near the beginning and maximum area near the middle of the duration categories. Most of the area curves of the STS-51J events were divided between the maximum peak at the middle, maximum peak near the end, and maximum peak near the beginning of the lifetime categories, with 25%, 23%, and 21%, respectively in each category.

IV. DISCUSSION

1. Uncertainties in Lightning Measurements.

Several analysis problems arise when trying to establish the dimensions of the lightning events which appear on the video tapes. These problems, discussed in sections 4.1a-4.1d include photogrammetric distortions, interpretation of brightness and the extent of a flash, camera threshold, blooming and residual image, and the scattering and absorption of the light produced by the lightning, by cloud particles.

a) Photogrammetric distortions.

The geometric approach to this analysis, explained in the appendix, should minimize the effects of image distortion caused by the camera pointing at some angle away from nadir. The greatest uncertainty in the interpretation of the size of the flash images occurred with the STS-9 events, because the limb of the earth was not visible, and the camera angle with respect to nadir was unknown. In this case, the assumption was made that the camera was directed at nadir.

The dimensions of the events of STS-9 are not unreasonable when compared to those events which were photographed with a zoom lens directed at nadir on the STS-51J video. In fact, flashes of a comparable size were found on the other three flights. However, on average the dimensions of the events of STS-9 are at least an order of magnitude smaller than the average dimensions of the other flights. Conceivably, this difference in the average size of the

lightning may indicate that this storm system was weaker than the ones which were photographed on the other three videos. Alternatively, the assumption that the camera was pointed at nadir may have resulted in an underestimate of the size of the STS-9 events.

b) Interpretation of brightness and distinguishing the borders of an event.

There is sure to be some error in the calculated dimensions of the lightning due to the fact that the borders of an event are not always clearly defined. The image size not only depends on the extent of a flash, but also on the depth of a flash within a cloud, its duration, and the intensity of the illumination. Irregularities in cloud geometry also add to the problem in that some sections of a lightning channel may be more exposed than others due to crevices within the cloud top (Brook et al., 1984, Vaughan, 1984, and Christian et al., 1983). There is also a possibility that several events, which occur simultaneously, may be interpreted as one large flash if they are located near each other.

c) Video camera induced errors.

Some possible causes of camera induced errors in the lightning measurements involve the triggering threshold, the rate at which each frame was exposed, the existence of residual images, and image blooming. It seems likely that there were events which were too faint to be detected by the camera. As mentioned in section II, there were instances when the outline of a flash was difficult to distinguish from the background, because the event was so faint. It

also seems likely that there were events whose duration was shorter than the 33 ms frame exposure rate of the camera, and were therefore not resolved in time. Uman (1984) reports events with durations as short as 10 ms.

The STS-51J video camera was tested for residual images and blooming. A strobe flash, running at 100 rpm, was set up behind a 2mm diameter pinhole. The video camera was used to photograph the light coming through the pinhole in both an illuminated and dark room, from a distance of approximately 4.5 meters. After studying the video of the strobe flash, it was found that the image of the illuminated pinhole was not carried over between video frames. Thus, residual images should not be a problem in the space shuttle videos.

However, the video of the strobe light showed that blooming of the image occurred. Image bloom is uniform in all directions, and is a function of the intensity of an image. The image of the strobe light had a bloom of 0.25° when the lights were on, and a bloom of 0.38° when the room was dark. Let us assume that the worst case of blooming, 0.38° , occurred in the space shuttle videos. Although the number of degrees of bloom would be uniform in all directions on the image of a flash, the actual distance that this transforms into would not be uniform for the STS-8, STS-41D, and STS-51J videos. For example, a bloom of 1° on the edge of a flash which is nearest the limb of the earth represents a much larger distance than the same 1° bloom on the edge which is farthest from the limb of the earth. Therefore, the amount of error in the dimension of a flash

due to blooming depends on where the flash image is located, because the actual distance between two points varies over the field of view of the camera.

The errors in the dimensions of a given event, based on the worst case of blooming were calculated for each flight. Again, the actual error in flash dimensions is a function of the location of an event within the field of view. For the events of STS-41D, this worst case scenario of bloom would result in errors of 5km - 70km in the direction perpendicular to the limb of the earth, and 3km - 15km in the direction parallel to the limb. For the STS-51J video, the bloom would result in errors of 60km - 145km and 10km - 20km in the directions perpendicular and parallel to the limb of the earth, respectively. For the STS-8 events, the bloom would result in errors of 10km - 90km in the direction perpendicular to the limb, and 5km - 15km in the direction parallel to the limb. The error due to image bloom for the events of STS-9 ranges from 3 km - 4 km, while that for the STS-51J events which were photographed with the zoom lens ranged from 6 km - 7 km. These later two videos only have one pair of possible errors because the camera was looking straight down.

The amount of bloom cannot exceed the actual dimension of a flash image. A comparison of the average initial dimension of the major and minor axis of a flash (Table II) to the maximum value of bloom determined by the strobe test shows that in most cases, the maximum value of error due to bloom exceeds the value of the average initial dimensions. This is also true when comparing the

average maximum dimension of the major and minor axes of STS-8 and STS-51J (Table III) to the maximum possible bloom. It seems likely that the amount of blooming which occurred on the video tape was smaller than the maximum value given in the strobe test, and that for most events, errors due to blooming were small, compared to the size of a given event.

d) Errors due to absorption and scattering.

This section addresses the question of how much of the light, produced by a lightning event, is absorbed, how much is scattered, and what type of measurement errors are introduced into the analysis of the size of a flash by these two phenomena. In cloud models, Thomason and Krider (1982) have shown that the total absorption of visible light, produced by point and extended sources, is negligible in clouds with total optical depths of up to 400. It seems likely that absorption of the illumination produced by lightning is so small that errors in measurement due to this are infinitesimal.

The amount of scattered light from a lightning event which comes out of the top of a cloud is a function of the depth of the source. Thomason and Krider (1982) state that most intracloud discharges, and the in cloud portion of cloud-to-ground discharges occur at altitudes at or above the optical center of a cloud. This means that the amount of photons escaping the cloud top is high. Furthermore, they found that very little of the light produced by sources near the base of a cloud escapes through the top of that cloud. Most of it will escape out the base of the cloud. Therefore, it is possible that many flashes originating near the cloud

base would produce an illumination at the top of the cloud which is to faint to be detected by the video camera. It is also conceivable that some of the smallest flashes are not that small after all, but instead are located near the cloud base.

If the smallest event on any given video was assumed to be produced by a point source, then its dimensions would give an estimate of the extent of the scattering of the light produced by lightning. It would also indicate what type of errors due to scattering are involved in the measurements of the size of a flash. Based on the above assumption, the error due to scattering for STS-8, STS-9, STS-41D, and STS-51J events would be approximately 6km, 1km, 2km, and 2km, respectively.

Thomason and Krider (1982) defined the characteristic dimension of the flux density of photons escaping a given cloud surface to be that area whose dimensions bound the region through which approximately 70% of all photons escaping the cloud surface pass. In their cloud models, they found that the characteristic dimension of the flux density was typically 60% to 70% of the cloud dimensions, when the light source was greater than 0.25 scale units from the cloud surface. If the assumption is made that the largest of all lightning events, which extended approximately 400 km, was 60% to 70% of the total cloud dimension, then the cloud surface would be estimated to be 600 km wide. It is quite interesting that this particular event occurred in the video of typhoon Brenda, and that the estimated cloud surface size agrees nicely with the typical extent of a typhoon. Perhaps this event was due to lightning

traveling across the typhoon, connecting successive thunderstorm cells.

2. Composite Traces.

The composite traces appearing in Figures 5 through 9 not only show the shape and size of a flash, but also its direction of growth. At this time, it is not clear why some flashes grow outward in all directions, as in Figure 6A, and why others grow in a preferred direction (Figure 7A). It is also unclear why some flashes slowly build up to their largest extent, while others, like flash 2 of STS-41D (Figure 7B), are largest on their initial frame, and then proceed to decrease in size over a relatively long time period. Time traces allow one to get a feel for when simultaneous events appear with respect to each other, and how far apart they are. Conceivably some sort of breakdown process could be propagating from one simultaneous event to the other. The rate at which this breakdown process would travel varies from 10^5 msec^{-1} for most simultaneous events shown in the composite traces, to 10^6 msec^{-1} for coincident events 6/7 and 169/171 of STS-51J (Figures 8A and 9B).

3. Characteristics of the Lightning Events.

The following three sections discuss the duration of the flashes, their horizontal extent, and the rate of propagation of the illumination produced by the lightning events.

a) Duration.

The values of the average duration of the lightning events shown in section 2.1 for all flashes, and for each flight are close to the average values found in Clifton and Hill (1980), Turman (1979), Orville (1982), Malan (1956), Smith (1957), and Brook and Kitagawa (1960). In this study, the duration of the flashes ranged from 33 ms to 1833 ms. This range of values falls well within the range given in Uman (1984) for lightning flash durations.

One would expect the thunderstorms associated with typhoon Brenda (STS-51J) to have had extensive vertical development. Brook and Kitagawa (1960) have suggested that the duration of a flash is related to the vertical convective activity of a storm, and is proportional to the average amount of charge involved in the discharges. It is interesting that over 70% of the flashes whose duration was greater than 800ms appeared in the STS-51J video. The fact that most of the flashes with a long duration and large horizontal extent (those with dimensions greater than or equal to 100 km), occurred in the STS-51J storm system supports this idea.

The average time interval between two consecutive flashes was 24 sec. for STS-41D, 1.5 sec. for STS-9, 0.9 sec. for STS-51J and 3.4 sec. for STS-8. With the exception of STS-8 events, the greater the mean duration of the flashes, the greater the frequency of lightning events. Brook and Kitagawa (1960) showed this same relationship to be true for isolated cloud systems of limited horizontal extent.

b) Extent of the region illuminated by lightning.

The average initial and largest dimensions of the lightning events investigated in this study (Tables II and III), agree reasonably well with the dimensions of the events observed in the earlier shuttle flights STS-2, STS-4, and STS-6. Vonnegut et al. (1983a), Vonnegut et al. (1983b), Vonnegut et al. (1984), and Vonnegut et al. (1985) reported flashes whose dimensions ranged from approximately 2 km x 2 km to 60 km x 40 km, with a maximum extent of 100 km. Vaughan et al. (1984) reported a flash with dimensions of approximately 75km x 40km. In other studies investigating the horizontal extent of lightning, Ligda (1956) reported flashes which extended 80 km to 160 km, while Teer and Few (1974) found that in the dissipating stage of a thunderstorm, intracloud flashes had an average horizontal extent of 11 km, with a maximum of 19.8 km. They also found that the in-cloud portion of a cloud-to-ground flash had an average horizontal extent of approximately 10km, with a maximum of 12km.

The average dimensions of the lightning of STS-41D were the largest of all flights. However, the sample size of only 8 events is quite small when compared to the number of events seen in the other videos. Therefore, the small sample size may have some influence on the values of the average dimensions of these events. The STS-41D events were unique in that they maintained their peak size for a period of 100 ms or longer. The largest of all events appeared on the STS-51J video. The great size of this event is most likely due to the intense thunderstorms associated with typhoon Brenda.

Vonnegut et al. (1985) reported a lightning event with a maximum area of $5 \times 10^3 \text{ km}^2$. The astronauts have reported lightning events which they estimated to extend to regions as large as 10^6 km^2 (Vonnegut et al., 1984). Teer and Few (1974) report lightning events whose average maximum area was 18 km^2 . 90% of the events from the four videos in this study had areas from 1 km^2 - $5,000 \text{ km}^2$. The average maximum area of the illumination was 1870 km^2 , for all flashes. This value agrees reasonably well with the value given in Vonnegut et al. (1985).

It is not clear why the average values of the initial and maximum area, for the flashes of STS-9, are one to two orders of magnitude smaller than the average initial and largest areas of the other three flights. As previously mentioned, the possibility of an error in flash dimensions due to assuming the camera was pointed directly at nadir exists. Even if a correction, as stated in section 2, of a factor of two was applied to the measurements of the STS-9 events, they would still have average dimensions which are much smaller than those of the other flashes in this study. This may imply that the events in this video occurred in smaller thunderstorms, or in storms which were in their dissipating stage, much like those observed by Teer and Few (1974).

The average initial area of the STS-41D flashes was an order of magnitude larger than that of STS-8 and STS-51J, while the average largest area of the STS-41D events was nearly double that of STS-8 and STS-51J events (Table III). Again, this difference is likely to be dependent on the small sample size of events, as five of

the eight STS-41D flashes had initial and maximum areas which were typical of the flashes in the STS-8 and STS-51J videos. The other three STS-41D events had maximum areas greater than 10,000 km². It is very interesting that three events of this size occurred within a one and one-half minute time interval.

The average ratio of the largest to the initial area of an event was 8.0, for all flashes. This gives an indication of the extent of growth for the lightning. The fact that this ratio is so much smaller for the events of STS-41D (Table III) shows that these events were close to attaining their maximum extent when they first appeared.

The ratio of the maximum dimension of the major axis to the maximum dimension of the minor axis of a flash was also considered. This ratio had values of 3.3:2, 3.2:2, 3.5:2, and 4.1:2 for the events of STS-8, STS-9, STS- 41D, and STS-51J, respectively.

Teer and Few (1974) reconstructed 37 cloud-to-ground and intracloud lightning events by plotting the acoustic source points of the thunder produced by these events. They treated these acoustic source points as a probability ellipsoid in order to represent the lightning channel as a collection of points in space. The results of their study indicated that a typical ratio of the long horizontal axis, to the short horizontal axis, to the vertical axis was 3:2:1. It is interesting to see that the ratios of the major to minor axes of the flashes in the shuttle videos are close to the value of the ratio of the horizontal axes found by Teer and Few.

The large flashes which appeared in the STS-8, STS-41D, and STS-51J videos are of particular interest because accounts of lightning extending 100 km or more are few in the literature to date. In all, there were thirtyone lightning events which had at least one axis greater than 100 km. 74% of these large events occurred in the STS-51J video over typhoon Brenda. Even if corrections were made for scattering and image bloom, these events would still be quite large. For example, the largest event of STS-51J had dimensions of 440 km x 110 km. The smallest event on the STS-51J video was approximately 2km. If we assume this event was produced by a point source of light, then its dimension gives the approximate error due to scattering. In section 4.1c, the errors in determining the size of a flash due to image bloom were shown to range from 145km - 60km in the direction perpendicular to the limb of the earth, and 20km - 10km in the direction parallel to the limb of the earth. After correcting the measured dimensions for scattering and the worst possible error due to blooming, this flash would have dimensions of approximately 290km x 90km. These dimensions are still much larger than most of the values of the extent of a lightning event previously reported in the literature. In this particular case, the lightning channel would extend across almost half of the typhoon.

Several other reports of lightning events that were extremely large can be found in Vonnegut (1979), in which astronaut Paul Weitz's observation of an event extending 200 to 300 km is given, and in Vonnegut et al. (1984) in which a flash with a maximum

dimension of 100 km is reported. Ligda (1956) shows a photograph of a radar echo of a lightning event which was 160 km long. Davies et al. (1983) reports the eyewitness accounts of astronauts, who estimated the extent of some lightning events to be over 800 km.

If indeed these large flashes are produced by a single event, then the lightning channels must be moving from the charged region of one thunderstorm cell to that of another cell. The idea of a channel extending from one cell to the next is not a new one. Brook and Vonnegut (1960) have observed the up and outward movement of the junction (J) process in a thunderstorm. They observed the J streamer progressing in divergent horizontal directions, and concluded that lightning may bridge individual storm cells. Workman et al. (1960) reported a lightning event which had 26 return strokes, and a duration of two seconds. They suggested that this flash had a large extent, and involved four to six simultaneously active thunderstorm cells.

Ligda (1956) suggested that an intracloud or a cloud-to-ground event, of large horizontal extent, would move along a path of low resistance. He reasoned that large flashes would be located at high altitudes where the pressure is low, the atmosphere is less dense, the relative humidity (and liquid water content) is high, and thus the breakdown voltage would be lower. His conclusion was supported by the fact that the radar echos of the large lightning which he observed were located in regions of light precipitation echoes which were associated with the cloud anvil, and in or above the 6 km (20,000ft) level. The idea that these large events occur at high

altitudes is also supported by the cloud models of Thomason and Krider (1982). In these models, more of the light produced by a source located below the optical center of a cloud would escape through the base and sides of that cloud, than would escape through the top of a cloud. Therefore, it seems likely that in order to see a large region illuminated by lightning, the flash must occur above the optical center of the cloud.

Conceivably, the large flashes could belong to the family of lightning events known as superbolts, whose radiated energy is 100 time more intense than that of a typical lightning event (Turman (1977), Turman (1979), and Edgar (1983)). These flashes have been observed with Vela and DMSP satellites in the fall and winter months, and only in certain regions of the world. It is very interesting that the time of year in which the STS-8, STS-41D, and STS-51J videos were filmed coincides with the time of year that superbolts have been observed. Furthermore, the location of the lightning filmed in these videos coincides with regions in which high concentrations of superbolts have appeared. Turman (1977), HOWEVER, suggested that superbolts do not occur near the top of the cloud. He found that only one to three, of the four Vela satellites observing a common region, would detect the superbolt. This, he felt, implied that those satellites not detecting the event were selectively obscured from the flash by other clouds. If the superbolt occurred in the cloud top, all four satellites should have detected it. The idea that the large flashes do not occur in the cloud top conflicts with the ideas of Ligda (1956) which were

presented earlier.

Alternatively, these extremely large flashes may be the result of several events occurring at the same time, which the camera cannot resolve. However, flashes as small as several kilometers have been found, so it seems likely that camera resolution is not a problem. Assuming that the average diameter of a thunderstorm is 10 km, and that one flash can illuminate an entire cloud, then an illuminated region extending 300 km may have up to 30 discharges occurring simultaneously. Even if the large flashes are not one, but several events, then there must be some explanation as to why a large number of events are appearing simultaneously.

c) The rate of growth of the illumination.

On average, the rate of growth of the illumination from the initial to the largest dimension of a flash was on the order of 10^5 msec^{-1} , and ranged from $0.2 \times 10^4 \text{ msec}^{-1}$ to $5.9 \times 10^6 \text{ msec}^{-1}$. In 30 of the 37 events in which the 10^6 msec^{-1} rate of growth occurred, the maximum extent of the flash was attained on the initial video frame in which that event appeared. The flashes of STS-9, which had the smallest average dimensions, also exhibited the smallest average growth rate, while the flashes of STS-41D, which had the largest average dimensions, also had the largest average growth rate. The rates of growth of the illumination in this study are comparable to the values of the velocity of propagation of a leader that are found in the literature. However, the light recorded by the video was probably not from the extending leader. In Uman (1984), the velocity of a stepped leader ranges from $1 \times 10^5 \text{ msec}^{-1}$

to $2.6 \times 10^6 \text{ msec}^{-1}$, with an average value of $1.5 \times 10^5 \text{ msec}^{-1}$. Orville (1982) gives the rate of propagation of intracloud lightning as $2 \times 10^4 \text{ msec}^{-1}$, and the rate of propagation of the stepped leader of cloud-to-ground lightning as $1.5 \times 10^5 \text{ msec}^{-1}$, while Krider (1986) found the later to range from $4 \times 10^4 \text{ msec}^{-1}$ to $8 \times 10^5 \text{ msec}^{-1}$ with an average rate of $1.4 \times 10^5 \text{ msec}^{-1}$. Vonnegut et al. (1985) found that the rate of growth of the illumination from lightning events photographed on shuttle flights STS-2, STS-4, and STS-6 ranged from $4 \times 10^4 \text{ msec}^{-1}$ to $2 \times 10^6 \text{ msec}^{-1}$, with an average value of $3.5 \times 10^5 \text{ msec}^{-1}$. The values of the rate of propagation of the illumination for shuttle flights STS-8, STS-9, STS-41D, and STS-51J also agree reasonably well with the estimated rate of growth of lightning, viewed from space by astronaut Paul Weitz, of $5.8 \times 10^4 \text{ msec}^{-1}$ (Vonnegut, 1979).

4. The Relationship Between the Maximum Area of a Flash and its Duration, the Time that the Maximum Area Occurred, and the Percent of the Total Lifetime of an Event at Which the Maximum Area was Attained.

a) Duration versus the maximum area of a flash.

It seems likely that the larger the dimensions of a flash, the longer the lifetime of that flash will be, provided that a conductive channel is moving outward from the origin of the flash at a constant rate. Indeed, the data in Figures 17-19 strongly support this idea. These curves indicate a general trend of increasing average maximum size with increasing duration. This relationship suggests that on

average, the longer the duration of a lightning event, the larger the region of charge which is drained will be. When comparing the individual data points shown in Figures 14-16, however, we see agreement with Malan's (1956) conclusion that lightning events of long duration aren't necessarily draining more extensive regions of charge than shorter duration events. That is, when looking at individual data points we see that there are some larger flashes with a duration which is shorter than other events which are smaller in size.

b) When did the maximum area occur?

On average, for all events, it took 220 ms for a flash to attain its maximum area. The average time to attain the maximum area for each flight was 230 ms, 190 ms, 290 ms, and 70 ms for the events of STS-51J, STS-9, STS-8, and STS- 41D, respectively. These numbers raise an interesting question. That is, why did the flashes of STS-41D, on average, reach their maximum extent sooner than the events of the other flights, and is this somehow related to the fact that this group of events had such a large average maximum size? The data from this study do not give any clear answers to these questions.

Figures 24-26 indicate that the time in which the maximum size is attained increases slightly as the average maximum size of a flash increases. This relationship holds true for all flashes, as well as for the events of STS-51J, STS-9, and STS-41D, although it is stronger for the STS-51J events than for the later two. If we choose to ignore those data points in Figures 24-26 which represent

a single event before averaging the maximum areas (those at or beyond 600 ms for all flashes and STS-51J events, and those at or beyond 500 ms for STS-9 events), the trend of increasing maximum area with time becomes more strongly defined.

Although not shown, the curve of the time to maximum area versus the average maximum area for the events of STS-8 indicates a slight inverse relationship between these two variables. It is not clear why the lightning events of STS-8 do not follow the upward trend exhibited by the other sets of data.

c) The maximum area of a flash versus the percent of the total duration of the flash at which that maximum area occurred.

On average, for all flashes, the maximum extent of a flash was attained at 58% of the total duration of the flash. The average percentage of the total duration of the flash at which the maximum area occurred, for each flight, ranged from 33% to 61%. The lowest average percentage value corresponds to the flashes of STS-41D, which had the largest average area. The highest average value occurred in the events of STS-9, which had the smallest average area. Figure 31 indicates that as the average maximum area increases, the percent of the total duration of the flash at which the maximum area occurs decreases, for the lightning events of STS-9, and for all flashes. Although not shown, similar curves for the events of STS-41D and STS-8 also indicate this same general decreasing trend. That is, larger flashes reach their maximum extent earlier in their lifetime than smaller flashes. It is not clear at this time why the curve of the STS-51J events shown in Figure 31

does not follow the decreasing trend, but instead shows that the largest events attain their maximum extent at 60%-70% of their total duration.

Sections 4.4a-4.4c can be summarized by the following statement. In general, larger flashes have longer durations, take longer to attain their maximum area, and reach this maximum area at a smaller percent of their total duration than smaller flashes. Exceptions to this statement include the events of STS-51J, for which there was not an inverse relationship between the maximum size of a flash and the percent of the total lifetime at which that maximum area occurs, and those events of STS-8, for which larger flashes did not take longer than smaller flashes to attain their maximum area.

5. The Peaks in the Area Curve.

The following sections discuss the results which are shown by plotting the area of a flash over its lifetime. The number of fluctuations in the area curve are discussed, along with the significance of these fluctuations. The time interval between the peaks in the area curves, as well as the change in the area between peaks and from a minimum to the following peak in the curve are also discussed. The relationship between these changes in area and the time periods over which these changes occur will be considered.

a) The number of peaks per flash.

It was found that when the area of a lightning event was plotted over its lifetime, there were an average of 3.6 peaks in the

area curve per flash. Conceivably, these increases in the area of the illumination are indicative of the return strokes of a flash. Both the range and average values of the number of peaks per flash, for all flashes as well as those for each flight (Table V), fall well within the values of the number of return strokes per lightning event that are found in the literature. Uman (1984) gives an average of 3-4 return strokes per flash, with a range of 1-26 return strokes. Clifton and Hill(1980) found an average of 2.6 return strokes per flash, with a range of 1-10 return stroke. Mackerras (1973) found an average of 3 return strokes per lightning event, while Turman (1979) found that the typical number of return strokes per lightning event was 4 to 5. Workman et al. (1960) found that most events had 2-6 return strokes, and one event which had 26 return strokes. Malan (1956) studied lightning events which had 1-14 return strokes per flash, with most events having 2-4 return strokes.

Approximately 17% of all the lightning events in this study had 1, 2, or 3 peaks in the area curve. 18% of the flashes had 4 peaks, 9% had 5 peaks, 9% had 6 peaks, and 13% had 7-14 peaks in their area curve. These percentages resemble those of Malan (1956) in a study of the number of return strokes in 530 lightning events. Clifton and Hill (1980) found 39% of the lightning events which they observed had only one return stroke.

The majority of the flashes which had 7 or more peaks in their area curve were from the STS-51J video. Of the 40 events in this peak per flash category, only 4 were contributed by the STS-9 flashes and only 1 by the STS-8 events. If storms which are more

convective, generate greater electric fields, perhaps the result would be a greater frequency of events, and lightning events of a greater duration and with a greater number of return strokes. The fact that the events of STS-51J, which were filmed over typhoon Brenda, had longer durations and more peaks per flash in the area curve than any other set of flashes, supports the above suggestion. Also, the average time interval between two consecutive flashes was 0.9 seconds for the events of STS-51J, while the same time interval was 3.4, 1.5, and 24.0 seconds for the flashes of STS-8, STS-9, and STS-41D, respectively.

A comparison between the number of peaks in the area curve with the duration of an event showed that on average, the longer the lifetime of an event, the more peaks there were in its area curve. This relationship was true when all flashes were treated as a single data set, as well as for the events of each flight. Malan (1956) found that the greater the number of return strokes that a lightning event had, the longer its duration. The fact that a similar relationship exists between the number of peaks per flash and the flash duration, further supports the suggestion that the peaks in the area curves are associated with return strokes.

b) The time interval and absolute change in area between peaks in the area curve.

The average time interval between peaks in the area curve was found to be 110 ms, for all flashes. This value is approximately the same for each flight (Table V). Figures 32-34 illustrate that the number of interpeak time intervals exceeding 100ms decreases fairly

rapidly.

When comparing a given interpeak time interval to the corresponding average absolute change in the area between two peaks it was found that an increase in one was associated with an increase in the other, for all flashes. This relationship appears to be reasonable. That is, a streamer or conducting channel propagating at a constant rate, would illuminate a larger region, if it had more time to travel. This trend of an increasing time interval between peaks, as the average absolute change in the area increased was also found for the events of STS-9, STS-41D, and STS-51J. This relationship was, however, not exhibited by the events of STS-8, which indicated an opposite trend of a decrease in the time interval between peaks with an increase in the average absolute change in the area between peaks. It is not clear why this set of flashes does not follow the increasing trend exhibited by the other data sets.

The average absolute change in the area between peaks, for all flashes, was 1130 km^2 . The average absolute area change between peaks for STS-8 and STS-51J was nearly equal to this value, while that of STS-41D was approximately 2.5 times larger, and that of STS-9 was two orders of magnitude smaller.

c) The time interval to the first peak versus the time from subsequent minimums to peaks in the area curve.

The time to the initial peak in the area curve ranged from 33 ms to 266 ms. On average, this time interval lasted 67 ms, for all flashes. The values, found in the literature, of the time interval to

the first return stroke of a flash agree reasonably well with the range of values of the time to the initial peak in the area curve. Uman (1984) estimated the time to the first return stroke to be 20 ms, assuming a 3 km channel propagated at a rate of $1.5 \times 10^5 \text{ msec}^{-1}$. Clarence and Malan (1957) found a time interval of 4 ms-30 ms before the first return stroke occurred, while Kitagawa and Brook (1960) found that this time interval lasted 10 ms-150 ms, with a mean value of 50 ms. However, it seems unlikely that the camera could 'see' the stepped leaders because they are so faint.

Brook et al. (1980) found that changes in the electric field caused by a lightning event, corresponded to the optical pulses produced by that event. In a study of the electric field changes produced by lightning, Kitagawa and Brook (1960) found that the initial part of the electric field signature from an intracloud event usually lasted 100 ms-150 ms. They found that the initial part of the electric field changes (that part preceding the first return stroke), of a cloud-to-ground event, lasted 20 ms-30 ms in 94% of the cloud-to-ground events they observed. They also found that the time interval of the electric field changes preceding the first return stroke never exceeded 150 ms for cloud-to-ground lightning. Based on the results of the two studies mentioned above, if indeed there is a correlation between the illumination and the changes in the electric field produced by an event, then perhaps the 13% of all flashes, whose time interval to the initial peak in area exceeds 100 ms, are intracloud lightning events. This group of events not only had a longer time interval to their first peak, but they also had an

average duration which was 100 ms longer than the average duration of the events whose time interval to the initial peak in area was less than 100 ms.

For all events, the average time interval from a minimum to the following peak in the area curve was 51 ms. This average value does not include the time interval to the first peak. The minimum to peak area time interval ranged from 33 ms to 266 ms. For each flight, the average value of this time interval was smaller than that of the average time interval to the first peak in the area curve (Table V). It is not clear whether the difference in these average values is significant.

As previously suggested, the peaks in the area curve may coincide with a return stroke of a lightning event. The values of the minimum to peak area time interval found in this study agree reasonably well with the values of the interstroke time interval reported in previous lightning studies. Uman (1984) reported interstroke intervals ranging from 3 ms-100 ms, with an average value of 40 ms. Workman et al. (1960) found that the average duration of the time period between return strokes was 77 ms. Malan and Schonland (1951) found that the average time between return strokes was 30 ms. Malan (1956) found that the interstroke time interval ranged from 15 ms-700 ms, with most values falling in the 30 ms-50 ms range. Krider (1986) lists the time between strokes as 40 ms-80 ms while Smith (1957) gives a value of 100 ms. Christian et al. (1983) and Brook et al. (1984) found that the interstroke interval lasted tens of milliseconds. Clifton and Hill

(1980) found that the interstroke interval ranged from 33 ms-367 ms, with an average value of 72 ms, and Orville (1982) reports an interstroke time interval of 40 ms.

When comparing the minimum to peak area time interval for the events of each flight, it is interesting to see that the average value of this time interval for the events of STS-41D is 20 ms smaller than that of the average values of the three other flights (Table V). In fact, there were no minimum to peak time intervals greater than 100 ms in this group of flashes. This suggests that the electric field involved with the events of STS-41D was able to recharge more quickly than that of the other three sets of flashes.

d) The time interval from a minimum to a peak in the area curve versus the change in the area during that time interval.

The average change in the area of an event from a minimum to peak in the area curve was 1100 km^2 for all events. This value is nearly equal to the average absolute change in the area between two peaks of the area curve. For each flight, the average minimum to peak change in the area was also nearly equal to the corresponding average absolute area change between peaks.

As the minimum to peak time interval increases, a corresponding increase in the change in the area from a minimum to peak seems likely. Assuming that a lightning channel propagates at a relatively constant velocity, the longer the minimum to peak time interval, the larger the region which is illuminated. A comparison of the average minimum to peak change in the area to the corresponding time interval showed that in general, this relationship

was true for all flashes, as well as for each flight (Figures 39, 44, and 45). However, the increasing trend of the average change in area with increasing time interval was stronger for the STS-8, STS-9, and STS-41D events than it was for the STS-51J events and all flashes together. Of the four flights, STS-9 had the smallest overall average change in the area between a minimum to peak, while STS-41D had the greatest overall average change in area. However, the events of STS-9 had the greatest average minimum to peak time interval (section 3.4e), while the events of STS-41D had the shortest average value and range of the minimum to peak time interval. Almost all the flashes, with minimum to peak time intervals lasting 266 ms, were in the STS-9 data set.

6. Flashes Which had the Bright Spot.

The bright spots, described in section 3.5, appeared in 16% of all the lightning events. Several flashes from the STS-9 video had multiple bright spots. One possible cause of these bright spots is that more light is escaping through the cloud top in the region of the bright spot, simply because the depth of the cloud above the lightning channel in that particular region is shallower. For example, there may be a crevice or hole in the cloud top, similar to that which is reported in Brook et al. (1984). Or, a lightning channel may be passing between two thunderstorm cells, exposing part of the channel. The lightning channel may even be entirely located inside the cloud, but varying in its altitude. Those parts of the channel at higher altitudes would appear brighter. In each of

the above, the light emitted by a flash must travel through different thicknesses of cloud. As a result, greater scattering occurs where the depth of the cloud above the channel is greater, and therefore different amounts of light escape through the cloud top.

If this were the explanation for these bright regions, it seems reasonable to expect this group of events to have average duration and size characteristics that are similar to those of the events without the bright spots. However, the results shown in Table VI indicate that this is not the case. On average, the flashes with the bright spot lasted 1.5-2 times longer than those without it. The average maximum area attained by these events was approximately 4 and 9 times greater than that of the flashes without the bright region for the STS-8 and STS-9 events, respectively. The average maximum area of the STS-51J bright spot events was also slightly larger than that of those STS-51J events without the bright spot. The bright spot events of STS-9 and all flashes also exhibited a much longer average time period to the first peak in the area curve.

These differences in the basic flash characteristics suggests that these events are not only distinguished by the bright spot, but they are also formed in a manner which differs from those without the bright spot. Vonnegut et al. (1985) observed a persistent bright region in a Y-shaped flash which was photographed from shuttle flight STS-4. They suggested that the bright region may be the location of an initial cloud-to-ground lightning stroke, and that the discharge was propagating outward, horizontally from the bright region into the cloud. If this interpretation is correct, it implies

that the multispot events of STS-9 are flashes which have multiple channels to ground.

7. Simultaneous Flashes.

The notion that several lightning events, which occur close in time but are separated by large distances, may somehow be interdependent is not a new one. Astronauts have reported looking down on discharges which were sympathetic, and seemed to be triggering one another (Vonnegut, 1979 and Vonnegut et al., 1985). In another eyewitness account, astronauts observed lightning which appeared to have a collective organization, with the triggering of events occurring over large distances (Cooper, 1976). Workman, Brook, and Kitagawa (1960) observed a flash which they deduced must have extended to involve four to six thunderstorm cells. They suggested that a discharge from one charge center would be followed by discharges from neighboring centers in quick succession. Ligda (1956) suggested that an initial discharge could alter the electrical characteristics of a large enough volume of cloud such that other flashes would be triggered, after he observed lightning events on a radar scope which appeared in the same general area, but which occurred a few tenths of a second apart. In his models of thundercloud electric fields Nisbet (1983) found when charges were redistributed in breakdown, it could effect the electric field enough to cause breakdown elsewhere.

The large number of simultaneous events which were found in this study suggests that there is more than just chance involved in

the fact that two flashes are nearly coincident in time. Approximately 64% of all lightning events appeared with at least one, and up to five, other flashes. Only a very small percent of all simultaneous events appeared with more than two other events.

If indeed these coincident flashes are related, then the effects of one discharge may possibly influence the electric field of another thunderstorm as far away as 360km, which was the maximum distance between simultaneous events. On average, these events were 60km apart, with over half separated by less than 40km.

For all events, the average time interval between the appearance of a flash and its subsequent simultaneous event was approximately 190 ms. This implies that a breakdown process between two coincident events would propagate at a speed on the order of 10^5 msec^{-1} . It is interesting that on average, the events of STS-51J were separated by 100's of kilometers, while the coincident events of STS-9 and STS-41D were an average of 10's of kilometers apart. Also, assuming that a breakdown process did exist between two coincident events, then that for the STS-51J events was, on average, much faster than that of the STS-41D and STS-9 events. In fact, 23% of the flash pairs from STS-51J had a possible breakdown process which propagated at a rate on the order of 10^6 msec^{-1} . None of the breakdown rates calculated for STS-9 and STS-41D exceeded 10^5 msec^{-1} . If a breakdown process is indeed propagating from one flash to another, the results imply that this process can travel over larger distances in a hurricane type storm system.

Vonnegut et al. (1985) found a pair of coincident events in a videotape of lightning taken aboard shuttle flight STS-4. These two events were 82 km apart. In this case, a dielectric breakdown process from one event to the other would have traveled at 10^6 msec⁻¹. Vonnegut et al. offered several explanations of the existence of simultaneous events, which included: (1) that a high speed ionization process exists between two events; (2) that the flashes in the field of view are triggered by yet another which is outside the field of view; (3) that one flash is triggered by the electric field changes, or electromagnetic radiation produced by another event; and (4) that the appearance of events simultaneously are just chance occurrences. The explanation for simultaneous events given in Mazur (1982) is similar to number three above. He suggested that interdependent electric fields of neighboring storm cells was the cause of simultaneous events. Mazur reasoned that after a discharge in one cell caused the collapse of the electric dipole within that cell, a sudden change in the electric field vector of another cell may result, speeding or delaying the start of the next flash in that cell. The data from the STS-9, STS-41D, and STS-51J videos unfortunately do not clarify which of the above explanations for simultaneous events is correct.

In a statistical analysis of a series of lightning events, Mazur (1982) found that the probability of two events, in multicellular storms, to be associated increased if the time between events was less than 100 ms. 38% of all simultaneously occurring events appeared less than 100 ms apart. 48%, 29%, and 100% of the

simultaneous events of STS-9, STS-51J, and STS-41D, respectively, fit this criteria. In addition, there were eight successive events which did not appear with any other event, but which occurred less than 100 ms apart. Overall, 19%, of the 323 lightning events, would be considered to be associated, based on the criteria of the Mazur study.

8. The Shape of the Area Curve.

Plotting the fluctuations in the area of a lightning event over time allows one to see both the differences and similarities between two events. For example, the differences between the very large flashes of STS-41D (Figure 50), and those of STS-51J (Figures 51-52) are quite interesting. Why is it that the large events of STS-41D maintain their great dimension over a longer time period than those of STS-51J? Is it possible that although these events have a large size in common, they are formed differently and that the electric fields of the cloud(s) in which these events occur are sustained over different time periods?

The area curves in Figures 65-71 display the relationship in time between simultaneous events. This series of figures illustrate events which appeared at the same time, some which began and ended within the lifetime of another coincident flash, and simultaneous events whose ending and beginning overlap. These plots may offer one way of determining whether or not several illuminated regions, appearing together, are truly separate events. For example, the fluctuations in the area curves of simultaneous events 66 through 68

of STS-9 (Figure 71) are very similar. These three events also began and ended at the same time. Though they appear as three separate illuminated regions in the video, it seems very likely that these three events are actually part of the same lightning event, illuminating different parts of a thunderstorm.

It is not clear what the significance is of the five shapes of the area curves. Perhaps certain shapes are associated with cloud-to-ground events, while others are associated with intracloud lightning. These curves may even indicate positive flash events, or ones which have continuing currents. However, without some sort of ground based observing system simultaneously recording the electric field changes, it is extremely difficult to deduce what these curve shapes mean. As Figure 83 indicates, there is not a strong preference for any one curve category. It is apparent, though, that the 'bimodal' and 'other' type curves occur much less frequently than the three other curve shapes.

The curve shapes of certain groups of lightning events were investigated. For example, 44% of the area curves of the unusually large flashes had the maximum peak near the beginning of the lifetime of the event, while 33% of the curves of these large events fit into the 'other' category. 31% and 29% of the area curves, of the events with the bright spot, fit into the maximum peak in the middle of the lifetime category, and maximum peak at the end of the duration categories, respectively. 44% of the area curves of the flashes whose time interval to the first peak in the area curve was greater than 100 ms, fit into the maximum peak near the end

category, while 34% of these area curves fit into the maximum peak near the middle category. Even among these three specific types of events, there is an overlapping of the favored curve types.

Assume a conductive lightning channel was propagating outward in order to tap into concentrated pockets of charge. Each successive return stroke would be longer than the preceding return stroke. Conceivably, each successive peak in the area curve of this event would be larger than its predecessor, corresponding to the lengthening of the lightning channel. In this case, we would expect the area curves of events formed in this manner to be similar to the curves in the third shape category, that is those with the maximum area at or near the end of the events lifetime.

Alternatively, Workman et al. (1960), proposed that the luminosity and electrical activity of a lightning event decreases with each successive stroke. In this case, we would expect the area curves of events acting in this manner to be similar to the curves of the second category. That is, those whose first peak in the area curve is also the largest, with each successive peak decreasing in size.

Some of the curves, including the bimodal ones, have major peaks which are separated by peaks of a much smaller magnitude. Examples of these curves can be found in Figures 57, 64, 68 (flash 64), and 72. Perhaps these smaller fluctuations in the area are due to M components (Malan, 1956), or J strokes (Brook and Vonnegut, 1960 and Malan and Schonland, 1951). Malan (1956) defines M components as small increases in continuing current and luminosity

between strokes. When comparing the photographs of the same lightning event taken with both slow and fast moving cameras, Malan found that a series of M components appeared to look like a stroke of a flash, because the camera could not distinguish separate M components. This may also be occurring in the videos examined in this study.

Finally, the shape of the area curves could conceivably be random, and independent of the type of lightning flash. Perhaps the percent of curves in each group occurred just by chance. It will be very interesting to see if the lightning events filmed on future shuttle missions will have area curve shapes similar to those found in this study.

V. CONCLUSIONS

A geometric analysis of the space shuttle video tapes of nocturnal lightning revealed some interesting characteristics of these events. The lightnings were found to have dimensions ranging from approximately 1 km x 1 km to 440 km x 110 km. The 31 enormously large flashes whose dimension(s) exceeded 100 km are of particular interest. Lightning extending more than 100 km has seldom been reported in the literature. This group of flashes supports the suggestion of Vonnegut et al. (1985) that lightning can be a mesoscale phenomena. Although these large events appeared in all but the STS-9 video, most of them were associated with Typhoon Brenda. The location of these events, and the time of year that they occurred implies that these lightning events may be part of a family of lightnings called superbolts, which have been detected by Vela satellites.

On average, the 323 lightning events in this study had a duration of 400 ms, with values ranging from 33 ms to 1833 ms. With the exception of the STS-8 video, the greater the mean duration of the events of a given video, the greater the frequency of the events. This finding agrees with that of Brook and Kitagawa (1960). The average area of the region illuminated by the lightning was 1870 km^2 , and ranged from $.5 \text{ km}^2$ to 36900 km^2 . On average, the largest area illuminated by a flash was eight times greater than the initial area.

The rate of growth of the illumination from the initial to the largest dimension of a flash ranged from $0.2 \times 10^4 \text{ msec}^{-1}$ to $5.9 \times 10^6 \text{ msec}^{-1}$. The overall average rate of growth to the largest dimension was $3.5 \times 10^5 \text{ msec}^{-1}$ along the major axis of a flash and $1.8 \times 10^5 \text{ msec}^{-1}$ along the minor axis. These rates of growth are comparable to those found by Vonnegut et al. (1985) on earlier shuttle flights, and to the rate of propagation of a stepped leader (Uman, 1984).

On average, an event reached its maximum area in 220 ms, and at 58% of the total duration of the flash. A comparison of the maximum area of a flash to its duration, the time that the maximum area occurred, and the percent of the total lifetime of a flash at which the maximum area occurred showed that in general, larger flashes have longer durations, take longer to reach their maximum size, and attain their maximum extent at a smaller percent of their total duration than smaller flashes. Exceptions to this include the events of STS-8, for which larger flashes did not take longer to attain their maximum area, and STS-51J events for which the largest events attained their maximum area at 60% - 70% of their total duration.

Plots of the area of the lightning over time showed that on average there were 3.6 peaks per flash, with a range of 1 to 14 peaks. The number of peaks per flash, along with the length of the time interval between them suggests that the peaks are associated with the strokes of a lightning event. 70% of the events with seven or more peaks were from the STS-51J video. It is suggested that

the greater number of peaks in the STS-51J events may be related to the size of the storm cells associated with Typhoon Brenda. The results indicate that the greater the duration of an event, the greater the number of peaks in the area curve. This agrees with the findings of Malan (1956), that lightning flashes with a longer duration had more return strokes.

The time to the first peak in the area curve ranged from 33 ms to 266 ms, with an average value of 67 ms. These values agree reasonably well with those of the time interval to the first return stroke found in the literature. Based on the findings of Brook et al. (1980) and Kitagawa and Brook (1960), it is suggested that those flashes whose time to the first peak in area exceeds 100 ms are intracloud lightning events. The time from a subsequent minimum to peak in the area curve was found to last 33 ms to 266 ms, with an average value of 51 ms. For each flight, the average subsequent minimum to peak time interval was smaller than the average time interval to the initial peak in the area curve. This difference suggests that once a conductive channel is established, subsequent return strokes may propagate faster. In general, as the minimum to peak area time interval increased, the change in area over that time interval also increased. The average change in the area from a minimum to peak in the area curve was 1100 km^2 , for all events.

16% of all flashes had a bright spot. On average, this group of events had durations which were almost twice as long as the average duration of events without the bright spot. The average maximum area for these bright spot events was greater than that of

the events without the bright spot for the STS-8 and STS-9 flashes, while that for STS-51J and all flashes was approximately the same.

Approximately 64% of all flashes were simultaneous with one, and up to five other events. The great number of events appearing simultaneously may imply that these events are somehow related, as suggested in Vonnegut et al. (1985), Ligda (1956), and Nisbet (1983). If these simultaneous events are related, one discharge may effect another as far away as 360 km, although on average, these events were 60 km apart. If a breakdown process was occurring between two simultaneous events, it would be propagating at a rate on the order of 10^5 msec^{-1} . However, for 23% of the flash pairs from STS-51J this propagation rate would be on the order of 10^6 msec^{-1} . This suggests that this breakdown process can travel over longer distances in a highly organized storm system.

Plots of the area of a flash over time appear to fall into one of five curve shape categories. It is not clear at this time what the significance of these curve shapes is. Perhaps they identify whether an event is a cloud-to-ground, cloud-to-cloud, or intracloud lightning flash. The area curve shape may even indicate whether a flash has J strokes or M components. No single curve shape was highly favored over the others.

This research has left many questions unanswered. What is the significance of the bright spot? Why do some flashes get larger over time, while others attain their maximum area in the initial frame in which they appear? What is the meaning of the shapes of the area curves? Why do some events favor growth in a specific

direction, while others grow outward in all directions? It is my hope that future studies of this type will be able to answer some of these questions. It will be interesting to see if the lightning events observed on future shuttle flights have the same characteristics as those events studied here. Perhaps future observations will be made by cameras with a higher resolution, and which are triggered by a lightning event to run a certain number of minutes after an initial flash occurs. An automated camera system would allow a greater amount of flashes to be observed. Perhaps the camera could even be linked to a sensor which would record the camera angle with respect to nadir. This would allow for a more accurate analysis of the data. Finally, perhaps in the future, the space shuttle camera will be used to observe lightning events which are being simultaneously observed by a ground based lightning detection system, such as that described in Orville et al. (1983). Doing this may solve some of the questions left unanswered by this study.

REFERENCES

- Baldwin, R. R., W. F. Eichelman, R. J. Jost, and M. F. McKay, Eds., 1981: OSTA-1. NASA, Lyndon B. Johnson Space Center, JSC-17059., 35pp.
- Brook, M, and N. Kitagawa, 1960: Some Aspects of Lightning Activity and Related Meteorological Conditions. **J. Geophys. Res.**, **65**, 1203-1210.
- _____, and B. Vonnegut, 1960: Visual Confirmation of the Junction Process in Lightning Discharges. **J. Geophys. Res.**, **65**, 1302-1303.
- _____, R. Tennis, C. Rhodes, P. Krehbiel, B. Vonnegut, and O. H. Vaughan, Jr., 1980: Simultaneous Observations of Lightning Radiations From Above and Below Clouds. **Geophys. Res. Letters**, **7**, 267-270.
- _____, C. Rhodes, O. H. Vaughan, Jr., R. E. Orville, and B. Vonnegut, 1984: Nighttime Observations of Thunderstorm Electrical Activity From a High Altitude Airplane. Nasa TM-86455, September 1984, 27pp.
- Cenker, Robert, 1986: Personal Communication.
- Christian, H. J., R. L. Frost, P. H. Gillaspy, S. J. Goodman, O. H. Vaughan, Jr., M. Brook, B. Vonnegut, and R. E. Orville, 1983: Observations of Optical Lightning Emissions From Above Thunderstorms Using U-2 Aircraft. **Bull. Amer. Meteor. Soc.**, **64**, 120-123.

- Clarence, N. D., and D. J. Malan, 1957: Preliminary Discharge Processes in Lightning Flashes to Ground. **Quart. J. Royal Meteor. Soc.**, **83**, 161-172.
- Clifton, K. Stuart, and C. Kelly Hill, 1980: Low-Light-Level Television Measurements of Lightning. **Bull. Amer. Meteor. Soc.**, **61**, 987-992.
- Cooper, Henry S. F., Jr., 1976: A Reporter at Large: Life in a Space Station-II. **New Yorker Magazine**, September 6, 1976, **52**, 34-70.
- Davis, M. H., M. Brook, H. Christian, B. G. Heikes, R. E. Orville, C. G. Park, R. G. Roble, and B. Vonnegut, 1983: Some Scientific Objectives of a Satellite-Borne Lightning Mapper. **Bull. Amer. Meteor. Soc.**, **64**, 114-119.
- Edgar, B. C., 1983: The Distribution of Lightning Superbolts. In **Proceedings in Atmospheric Electricity**, Lothar H. Ruhnke and John Latham, Eds., A. Derpak Publishing (Hampton, VA), 397-400.
- Kitagawa, N., and M. Brook, 1960: A Comparison of Intracloud and Cloud-to-Ground Lightning Discharges. **J. Geophys. Res.**, **65**, 1189-1202.
- Krider, E. Philip, 1986: Physics of Lightning. In **The Earth's Electrical Environment**, National Academy Press, Washington, D.C., 30-40.
- Ligda, Myron G. H., 1956: The Radar Observation of Lightning. **J. Atmos. Terr. Phys.**, **9**, 329-346.

- Mackerras, D., 1973: Photoelectric Observations of the Light Emitted by Lightning Flashes. **J. Atmos. Terr. Phys.**, **35**, 521-535.
- Malan, D. J., and B. F. J. Schonland, FRS, 1951: The Electrical Processes in the Intervals Between the Strokes of a Lightning Discharge. **Proc. Royal Soc. London, Series A**, **206**, 145-163.
- _____, 1956: The Relation Between the Number of Strokes, Stroke Intervals, and the Total Durations of Lightning Discharges. **Geofis. Pura Applic.**, **34**, 224-230.
- Mazur, Vladislav, 1982: Associated Lightning Discharges. **Geophys. Res. Letters**, **9**, 1227-1230.
- Nisbet, J. S., 1983: A Dynamic Model of Thundercloud Electric Fields. **J. Atmos. Sci.**, **40**, 2855-2873.
- Orville, R. E., 1981: Global Distribution of Midnight Lightning - September to November 1977. **Mon. Wea. Rev.**, **109**, 391-395.
- _____, 1982: Lightning Detection from Space. In **CRC Handbook of Atmospherics**, Vol. II, H. Volland, ed., CRC Press, Inc. (Boca Ratan, Florida), 79-97.
- _____, R. W. Henderson, and L. F. Bosart, 1983: An East Coast Lightning Detection Network. **Bull. Amer. Meteor. Soc.**, **64**, 1029-1037.
- _____, and _____, 1986: Global Distribution of Midnight Lightning: September 1977 to August 1978. **Mon. Wea. Rev.**, **114**, 2640-2653.
- _____, 1986: Lightning Phenomenology. In **The Earth's Electrical Environment**. National Academy Press, (Washington D.C.), 23-29.

- Sparrow, J.G., and E.P. Ney, 1971: Lightning Observations by Satellite. *Nature*, 232, 540-541.
- Smith, L. G., 1957: Intracloud Lightning Discharges. *Quart. J. Royal Meteor. Soc.*, 83, 103-111.
- Teer, Thomas L., and A. A. Few, 1974: Horizontal Lightning. *J. Geophys. Res.*, 79, 3436-3441.
- Thomason, L. W., and E. P. Krider, 1982: The Effects of Clouds on the Light Produced by Lightning. *J. Atmos. Sci.*, 39, 2051-2065.
- Turman, B. N., 1977: Detection of Lightning Superbolts. *J. Geophys. Res.*, 18, 2566-2568.
- _____, 1979: Lightning Detection from Space. *Amer. Sci.*, 67, 321-329.
- _____, and B. C. Edgar, 1982: Global Lightning Distributions at Dawn and Dusk. *J. Geophys. Res.*, 87, 1191-1206.
- Uman, Martin A., 1984: *Lightning*. Dover Publications, Inc., (Mineola, N. Y.), 298 pp.
- Vaughan, O. H., Jr., 1984: NASA Thunderstorm Overflight Program - Atmospheric Electricity Research: An Overview Report on the Optical Lightning Detection Experiment for Spring and Summer 1983. NASA TM-86468, November, 49 pp.
- _____, B. Vonnegut, and Shi-Hong Huang, 1984: Low Light Level TV Images of Lightning from Space. *Bull. Amer. Meteor. Soc.*, 65, 373.
- Vonnegut, B., 1979: Lightning Observations from Space. *Weather*, 34, 291.

- _____, 1982: Top Weather Event of 1981. Flight of the Space Shuttle. **Weatherwise**, **35**, 27-9.
- _____, O. H. Vaughan, Jr., and M. Brook, 1983a: Thunderstorm Observations from Space Shuttle. NASA TM-82530, June, 27 pp.
- _____, _____, and _____, 1983b: Photographs of Lightning from the Space Shuttle. **Bull. Amer. Meteor. Soc.**, **64**, 150-151.
- _____, _____, _____, and P. Krehbiel, 1984: Mesoscale Observations of Lightning from the Space Shuttle. NASA TM-86451, September, 20 pp.
- _____, _____, _____, and _____, 1985: Mesoscale Observation of Lightning from Space Shuttle. **Bull. Amer. Meteor. Soc.**, **66**, 20-29.
- Workman, E. J., M. Brook, and N. Kitagawa, 1960: Lightning and Charge Storage. **J. Geophys. Res.**, **65**, 1513-1517.

APPENDIX

Two methods of geometric analysis were used to calculate the size of a flash. One method was used when the camera was pointing directly at nadir. The other was used when the camera was tilted from nadir, and the limb of the earth appeared in the video frame. The size of the lightning flashes was determined in the following manner. The outline of the region illuminated by a flash was traced from the video screen. The trace of the flash was treated as an ellipse. The major and minor axes of the ellipse were measured. Each of these two distances was converted to an angle in the field of view of the camera which they subtended. The angle in the camera field of view, Ψ , describing the length of the axis of the ellipse was then matched to a corresponding angle measured with respect to nadir and the center of the earth, ϕ , which is subtended by the axis of a flash. The angle ϕ is then converted to the actual distance on the earth's surface.

The following describes in detail the geometric analysis that was used to calculate the dimensions of the lightning events. If we assume the dimensions of the video monitor screen to be proportional to those of the image plane of the video camera, a grid can be constructed to convert a distance D measured on the lightning trace (see Figure A1), to an angle Ψ in the camera field of view. In Figure A1, Ψ is the angle between the perpendicular to the principle point of the image frame and a ray drawn to any X location. In Figure A1, the distance D on the lightning trace subtends an angle

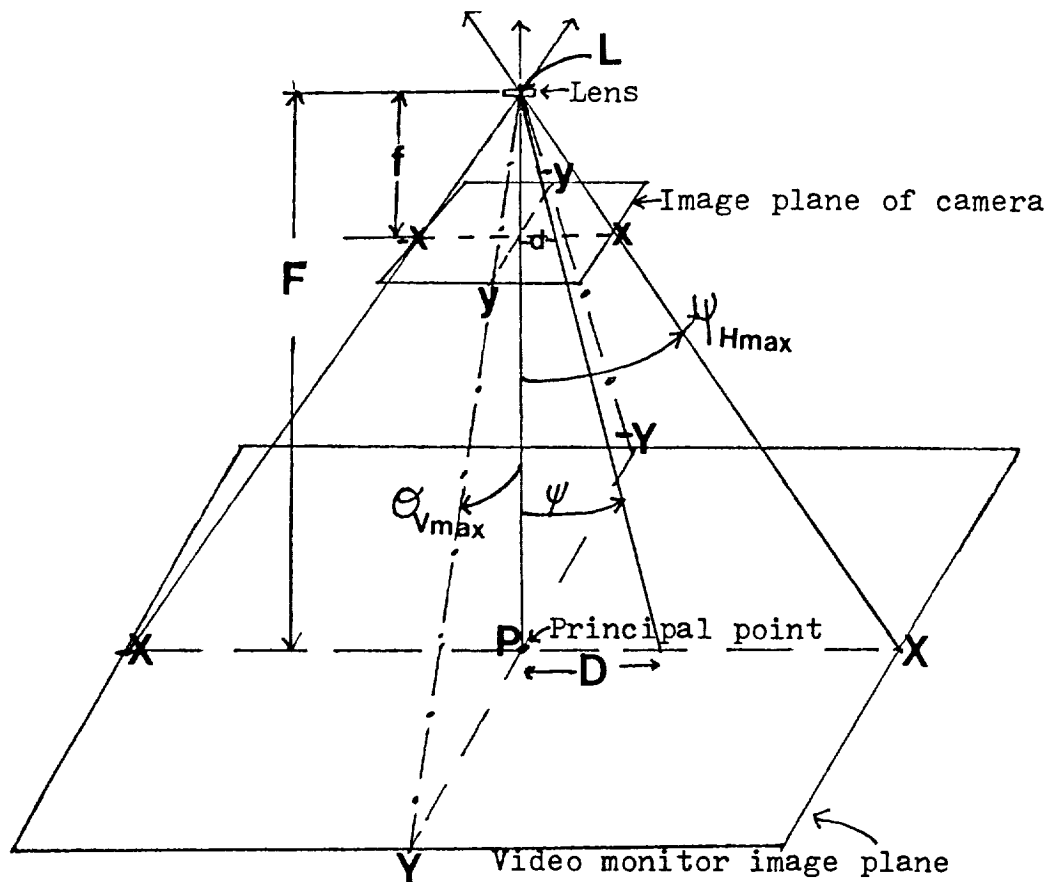


Figure A1: The geometric conversion of a distance D , on the video monitor, to an angle ψ in the field of view of the camera. ψ is the angle between the normal to the principal point P and a ray from point L to any X location. θ is the angle between the normal to the principal point P and a ray from L to any Y location, and is calculated in a similar manner to angle ψ . ψ_{Hmax} is equal to one-half the horizontal field of view, and θ_{Vmax} is equal to one-half the vertical field of view. The focal length of the camera is represented by f .

Ψ . Ψ can be found by

$$\Psi = \tan^{-1} \frac{D}{F} \quad (1)$$

F is calculated from one half the horizontal or one half the vertical fields of view, Ψ_{Hmax} and θ_{Vmax} , respectively, and the dimensions of the video monitor image plane by equations (2)

$$F = \frac{X_{max}}{\tan \Psi_{Hmax}} \quad (2)$$

or (3)

$$F = \frac{Y_{max}}{\tan \theta_{Vmax}} \quad (3)$$

For distances in the Y direction, the angle subtended by a given D is calculated by replacing Ψ in equation (1) with θ .

Most of the lightning images were elliptical in shape. Thus, the outline of the illumination was treated as an ellipse. The maximum extent of the major and minor axes were measured on the trace. Then the corresponding angles subtended by each axis were found. These angles, Ψ and θ , were then used to obtain the true dimensions of the flash. Two different methods of geometric analysis were applied, depending on whether or not the limb of the earth was visible.

When the video camera is pointed straight down at the nadir point with respect to the shuttle, photogrammetric distortions in

distance are negligible. Figure A2 illustrates this case. The field of view in the X direction is $2\psi_{Hmax}$, while that in the Y direction is $2\theta_{Vmax}$. The shuttle is at a height H above the earth of radius R. For every angle ψ , measured from the trace of the lightning, there is a corresponding angle ϕ measured with respect to nadir and the center of the earth. Likewise, for every $d\psi$, there will be a $d\phi$. Applying the law of sines to Figure A2

$$\frac{R}{\sin \psi} = \frac{r}{\sin \phi} \quad (4)$$

and by the Pythagorean theorem

$$r = [(H+R)^2 + R^2 - (H+R)2R\cos \phi]^{1/2} \quad (5)$$

By substituting equation (5) into (4), we can solve for ψ as a function of ϕ , resulting in

$$\psi = \sin^{-1} \left(\frac{R \sin \phi}{[(H+R)^2 + R^2 - 2R\cos \phi (H+R)]^{1/2}} \right) \quad (6)$$

where ϕ is determined by iterative calculations in 0.001° increments until a match with ψ is attained. ϕ ranges from 0° to ϕ_{max} and

$$\phi_{max} = 180^\circ - \psi_{Hmax} - \sin^{-1} \left(\frac{(H+R) \sin \psi_{Hmax}}{R} \right) \quad (7)$$

In equation (7), ψ_{Hmax} is equal to one half the maximum horizontal field of view. By replacing ψ with θ , and ψ_{Hmax} with θ_{Vmax} in equations (4) through (7), one can also solve for θ as a function of ϕ . After calculating the ϕ 's which correspond to the ψ 's of the

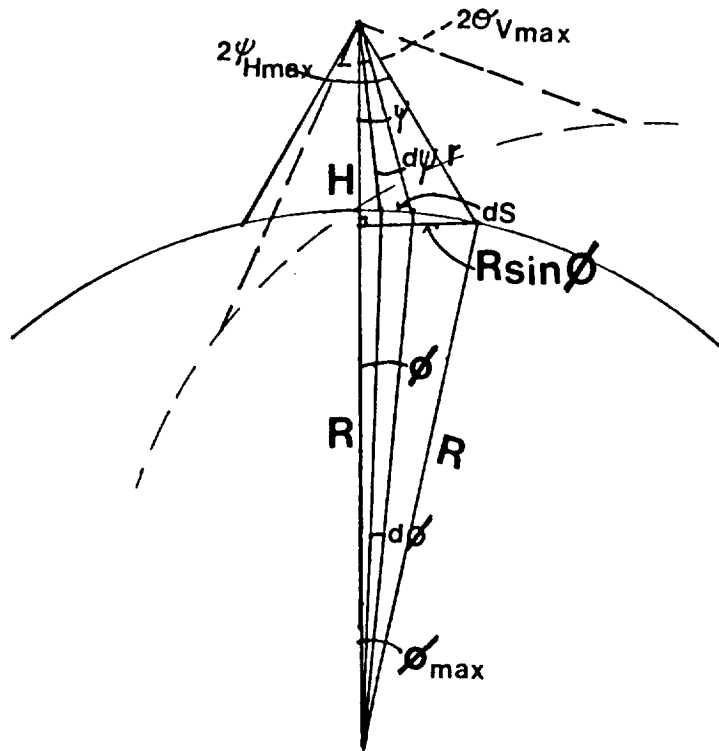


Figure A2: The geometric conversion of an angle in the field of view to an actual earth distance. The shuttle is at an altitude H above the earth of radius R . Every angle $d\psi$ has a corresponding angle $d\phi$. The actual dimensions of a flash, dS_{θ} and dS_{ψ} are found using equations 8a and 8b. This conversion is used when the camera is looking at nadir.

horizontal field of view, and the ϕ 's which correspond to the θ 's of the vertical field of view, the actual dimensions, dS_{θ} and dS_{ψ} , can be computed by

$$dS_{\theta} = R d\phi (\theta) \quad (8a)$$

$$dS_{\psi} = R d\phi (\psi) \quad (8b)$$

where $d\phi$ is in radians and dS and R are in kilometers.

When the limb of the earth appears in the video frame, it indicates that the camera was tilted at some angle away from the nadir point. This tilt results in a large distortion in distance in the direction normal to the limb of the earth. In this case, a $d\theta$ close to the nadir point of the shuttle will give a smaller actual distance than the same $d\theta$ located close to the limb of the earth, even though the distance on the image plane is the same (Figure A3). To correct for this distortion, θ 's on the image plane are measured from the limb of the earth, rather than from the principle point of the image plane. The corresponding ϕ 's are measured from the normal to the ray within the field of view which is tangent to the limb of the earth, Y , as illustrated in Figure A4. A' is a ray within the field of view which is tangent to the limb of the earth. Applying the Pythagorean theorem

$$A = [(R+H)^2 - R^2]^{1/2} \quad (9)$$

where R is the radius of the earth and H is the altitude of the shuttle. From Figure A4

$$\tan \theta = \frac{R - Y}{A - X} \quad (10)$$

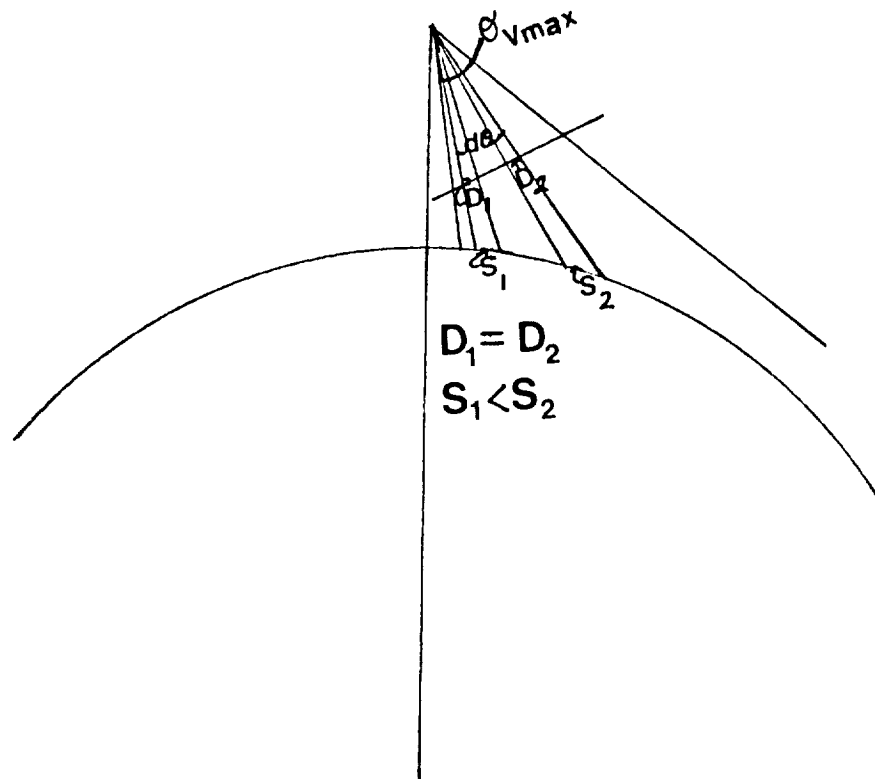


Figure A3: When the camera is tilted from nadir, then large distance distortions occur in the direction in which the camera is tilted. Consider an angle $d\theta$, taken at two different places within the field of view of the camera. Although the distances on the image plane, D_1 and D_2 , are equal, the corresponding actual distances, S_1 and S_2 are not equal.

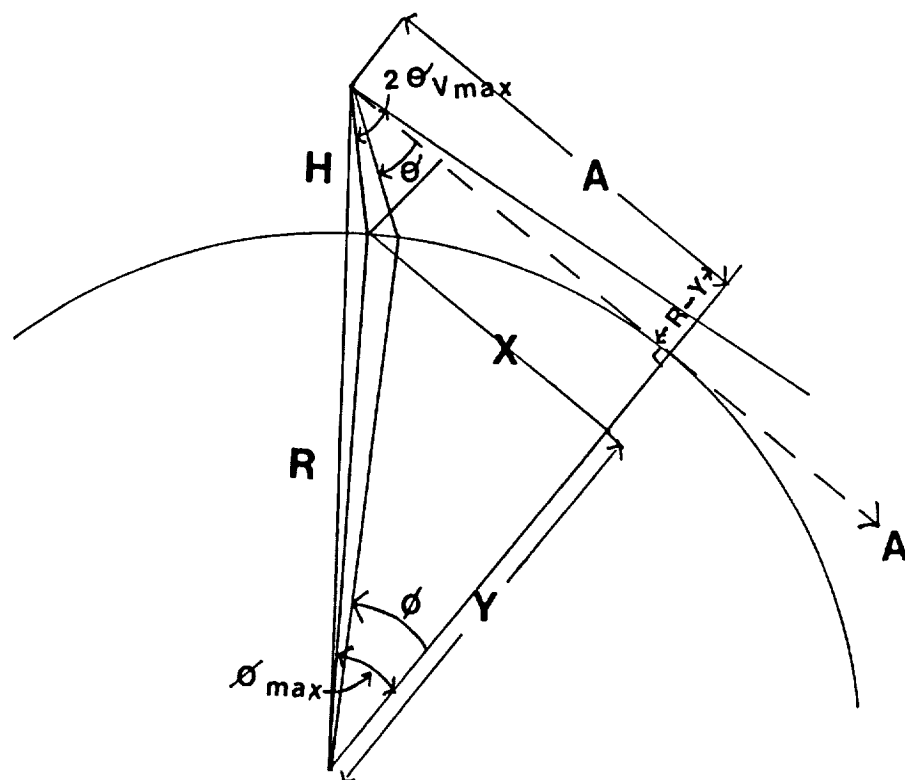


Figure A4: The geometric conversion of an angle θ , in the field of view, to the angle ϕ . The shuttle is at an altitude H above the earth of radius R . In this case, the camera is tilted from nadir. $2\theta_{vmax}$ is the vertical field of view. The angle θ is measured from the ray A' , which is a ray within the field of view that is tangent to the limb of the earth.

$$X = R \sin \phi \quad (11)$$

and

$$Y = R \cos \phi \quad (12)$$

Substituting equations (9), (11), and (12) into equation (10), we can express θ as a function of ϕ , where θ is measured from the tangent to the limb of the earth by

$$\theta = \tan^{-1} \left(\frac{\frac{1 - \cos \phi}{[(R+H)^2 - R^2]^{1/2}}}{\frac{R}{R} - \sin \phi} \right) \quad (13)$$

Again, ϕ is determined by iterative calculations until a match with θ is attained. ϕ was measured in increments of 0.001° . The actual length of the axis of the illumination which is normal to the limb of the earth can be found using equation (8a). To get the actual length of the axis which lies parallel to the limb of the earth, one must first find the average of the ϕ values which define the extents of the flash axis which is normal to the limb, and subtract it from ϕ (see Figure A5). The dimension of the flash axis which is parallel to the limb can then be found by

$$dS_\psi = R \sin \phi' d\psi \quad (14)$$

where $d\psi$ is the angle subtended by the flash in the direction parallel to the limb of the earth and is measured in radians. ϕ' is the difference between ϕ and the average of the two values, ϕ_1 and ϕ_2 , which are used to measure the flash axis in the direction perpendicular to the limb. R is in kilometers.

The second method of analysis was applied to the video tapes from flights STS-8, STS-41D, and that part of the STS-51J video which was photographed with the 25 mm lens. The flashes of STS-9, as well as the sequence of lightning flashes photographed with the zoom lens in the STS-51J video, were analyzed by the first method.

Most of the flashes had an elliptical shape. Therefore, the areas of the lightning were calculated by

$$A = 1/2 dS_{\theta} * 1/2 dS_{\psi} * \pi \quad (15)$$

where A is in km². When part of the flash was off the screen of the monitor, its area was estimated by

$$A = dS_{\theta} * 1/2 dS_{\psi} * \pi \quad (16a)$$

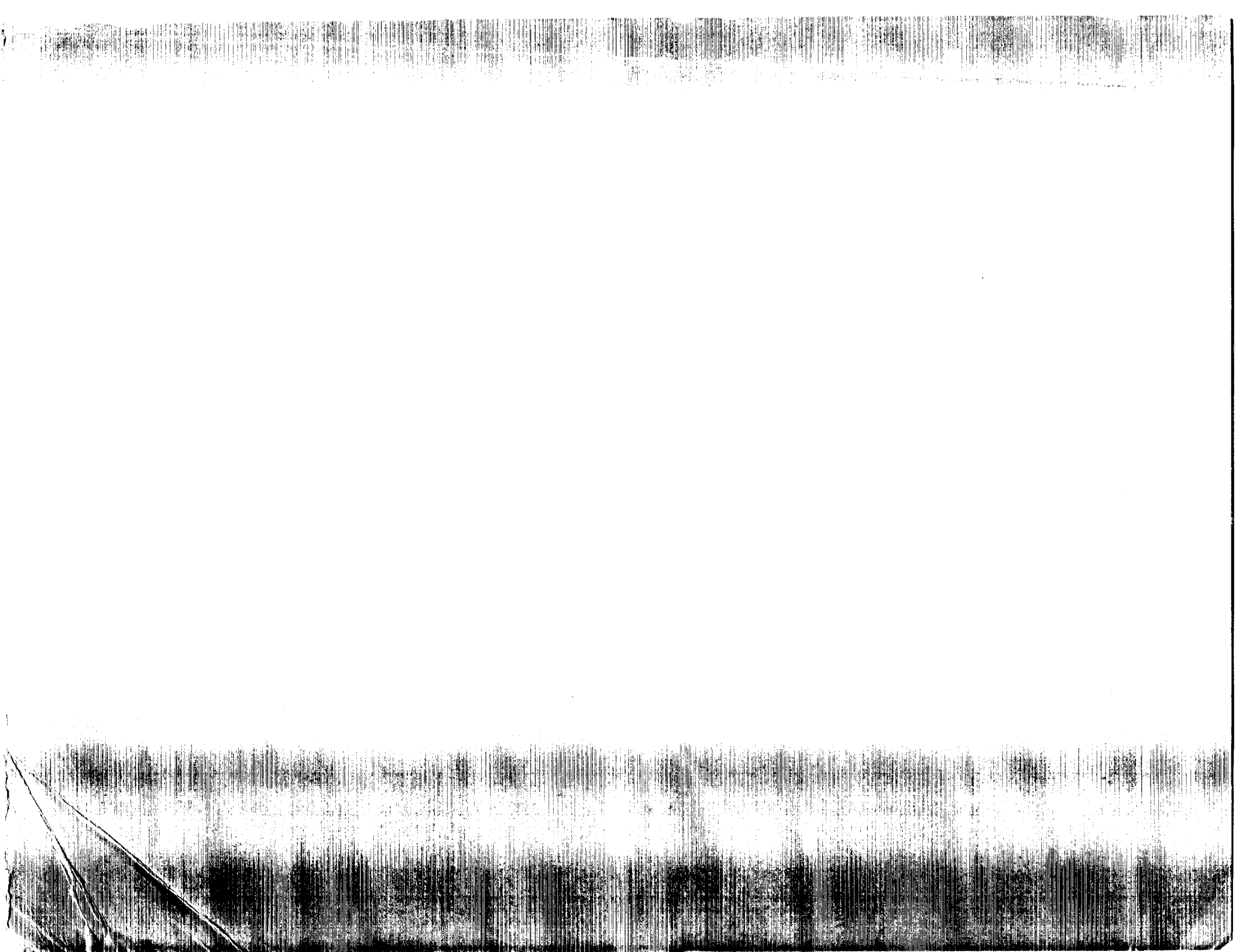
if the flash was off the top or bottom of the screen, and

$$A = 1/2 dS_{\theta} * dS_{\psi} * \pi \quad (16b)$$

if the flash was off the left or right of the screen.

Report Documentation Page

1. Report No. NASA CR-4313		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle Size, Duration, and Rate of Growth of Nocturnal Lightning Events Appearing on Space Shuttle Video Tapes				5. Report Date August 1990	
				6. Performing Organization Code ES43	
7. Author(s) Christine Breslawski				8. Performing Organization Report No.	
				10. Work Unit No. M-641	
9. Performing Organization Name and Address College of Science and Mathematics Department of Atmospheric Science State University of New York at Albany Albany, NY 12222				11. Contract or Grant No. NAS8-32893	
				13. Type of Report and Period Covered Final Report	
12. Sponsoring Agency Name and Address George C. Marshall Space Flight Center Marshall Space Flight Center, AL 35812				14. Sponsoring Agency Code	
15. Supplementary Notes Prepared for Space Science Laboratory, Science and Engineering Directorate. COR: O. H. Vaughan, Jr.					
16. Abstract An analysis of video tapes of nocturnal lightning events, taken aboard space shuttle flights STS-8, STS-9, STS-41D, and STS-51J, shows flashes with dimensions ranging from approximately 1 km x 1 km to 440 km x 110 km. Of particular interest are the flashes whose dimensions exceeded 100 km, as flashes of this size are seldom reported. In general, larger flashes were found to have longer durations, take longer to reach their maximum extent, and reach their maximum extent at a smaller percent of their total duration than smaller flashes. Sixty-four percent of the flashes occurred with one to five other events appearing in the same video frame. These simultaneous events were an average of 60 km apart from each other. If a breakdown process is propagating between the simultaneous flashes, it would be traveling at a rate of 10^5 ms^{-1} . Plots of the area of an event over its duration show peaks in the area curve which may be indicative of lightning strokes. There was an average of 3.6 peaks per flash. In general, the longer the flash duration, the more peaks there were in the area curve. The area curves of the lightning events fall into one of five shape categories. It is suggested that the shape of the area curve may indicate whether an event is an intracloud or cloud to ground lightning flash. Some of the lightning events had a persistent bright spot. These events had an average duration which was greater than that of events without the bright spot. On average, the bright spot events had a maximum area which was larger than that of the flashes without the bright spot.					
17. Key Words (Suggested by Author(s)) Space Shuttle, Mesoscale Lightning, Remote Sensing, Atmospheric Electricity				18. Distribution Statement Unclassified--Unlimited Subject Category: 47	
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of pages 230	
				22. Price A11	



NASA

National Aeronautics and
Space Administration

Washington, D.C.
20546

**SPECIAL FOURTH CLASS MAIL
BOOK**

Postage and Fees Paid
National Aeronautics and
Space Administration
NASA-451

Official Business
Penalty for Private Use \$300



LI 001 DR-4313 9007318090369A

NASA

SCIEN & TECH INFO FACILITY
ACCESSIONING DEPT

P O BOX 8757 BWI ARPRT
BALTIMORE MD 21240